Studies in Systems, Decision and Control 186

M. Hadi Amini
Kianoosh G. Boroojeni
S. S. Iyengar
Panos M. Pardalos
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Sustainable Interdependent Networks II

From Smart Power Grids to Intelligent Transportation Networks

Springer

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"This book presents an extremely valuable resource, the first of its kind, for scientists and engineers in addressing all critical aspects of interdependent power and transportation networks in a well-organized and strategic manner."

Prof. M. C. Frank Chang,
President of the National Chiao Tung University, Taiwan

"This book conducts an all-inclusive investigation of the interdependent power and transportation networks. I highly recommend this interesting book to those who are exploring futuristic but realistic ideas."

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"The second volume of Sustainable Interdependent Networks depicts a thorough path towards developing sustainable smart cities, as well as introducing modern computational platforms to find the globally optimum operation point of the interdependent power and transportation networks."

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"Sustainable Interdependent Networks II succeeds to tackle the future challenges of smart cities with the emphasis on interdependent power and transportation networks. It is recommended to scholars from electrical engineering, computer science, civil engineering, and industrial engineering disciplines who seek to perform research in the state-of-the-art interdisciplinary research areas."

Prof. Jose C. Principe, Distinguished Professor,
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"This book bridges the gap between theory and practice by providing a profound vision of interdependent networks. The second volume is specifically zooming into smart electric grids and intelligent transportation networks as subsets of smart cities. I would recommend this book for researchers who are eager to work on cutting-edge topics on the intersection of various disciplines, including system engineering, electrical engineering, computer science, and transportation engineering."

Prof. Sartaj Sahni, Distinguished Professor,
Computer and Information Sciences and Engineering,
University of Florida, USA; IEEE Fellow, ACM Fellow,
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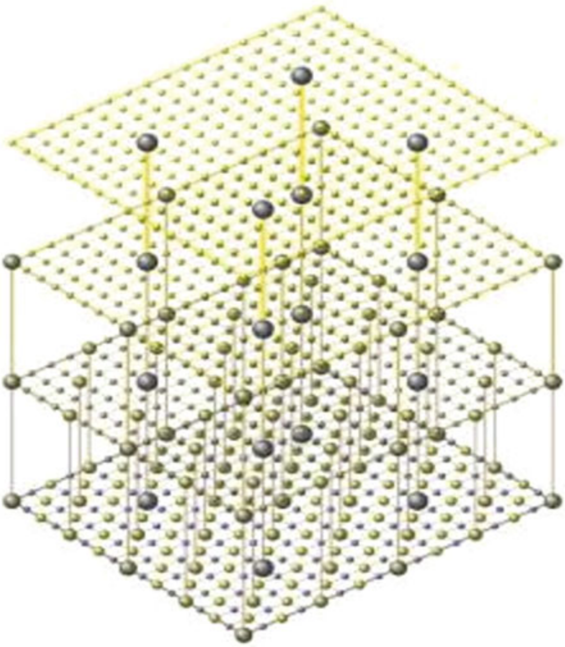
Preface



Since the concept of Internet of Things leading to smart cities, smart grids, and other technologies emerged, there has been a need to move towards a sustainable way of utilizing the technologies. Researchers have tried to answer this question on the emerging concern regarding the optimal operation of real-world large-scale complex networks. A smart city is a vision of the top brass of researchers to integrate multiple information and communication technologies in a secure fashion to manage a city's assets including transportation systems, power grids, distributed sensor networks, water supply networks, and other community services. Our reliance on these complex networks as global platforms for sustainable cities and societies as well as shortage of global nonrenewable energy sources has raised emerging concerns regarding the optimal and secure operation of these large-scale networks. Although the independent optimization of these networks leads to locally optimum operation points, there is an exigent need to move toward obtaining the globally optimum operation point of such networks while satisfying the constraints of each network properly.

There has been an emerging concern regarding the optimal operation of power and transportation networks. In the second volume of *Sustainable Interdependent Networks* book, we focus on the interdependencies of these two networks, optimization methods to deal with the computational complexity of them, and their role in future smart cities. We further investigate other networks, such as communication networks, that indirectly affect the operation of power and transportation networks. Our reliance on these networks as global platforms for sustainable development has led to the need for developing novel means to deal with arising issues. The considerable scale of such networks, due to the large number of buses in smart power grids and the increasing number of electric vehicles in transportation networks, brings a large variety of computational complexity and optimization challenges. Although the independent optimization of these networks leads to locally optimum operation points, there is an exigent need to move toward obtaining the globally optimum operation point of such networks while satisfying the constraints of each network properly.

The book series, including the first volume that has been published in early 2018, aims at covering wide areas from theoretical toward practical aspects of interdependent networks. Volumes I and II of this book cover different aspects of interdependent networks categorized in the following five categories:

1. Classic Optimization and Control Problems—consisting of research articles from outstanding researchers in the field that discusses and provides an insight into the classical and theoretical problems that exist in optimization and control.
2. Efficient Methods for Optimization Problems in Large-Scale Complex Networks: From Decentralized Methods Toward Fully Distributed Approaches—A more advanced outlook and possible methodologies that could be incorporated in large networks using various approaches are highlighted through manuscripts from leading researchers in this field.
3. Modeling the Interdependency of Power Systems, Communication Networks, Energy Systems (e.g., Gas, Renewables), Transportation Networks, Water Networks, and Societal Networks—The ways in which sustainable interdependence can be achieved across the various networks that span the horizons of smart cities are explained mathematically in terms of models that could be implemented. All the articles in this section deal with the interdependency of at least two networks that are an integral part of realizing a smart city.
4. Application of Power and Communication Networks: Co-simulation Platforms for Microgrids and Communication Networks, and Smart Grid Test Beds—The

various papers under this topic highlight the state-of-the-art technologies that are in place in the area of smart grids.

5. Application of Sustainable Interdependent Networks in Future Urban Development: The Tale of Smart Cities—This section constitutes papers that discuss the aspects to be pondered in the future and the direction in which the current school of researchers are heading toward realizing ideal sustained and interdependent networks in the future.

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Gainesville, FL, USA	Panos M. Pardalos
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Acknowledgments

The editors express their deepest gratitude to the professional colleagues who have contributed to this book, the agencies that have funded the relevant research, and to their families for their continued support.

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His current research interests include interdependent networks, distributed/decentralized optimization algorithms in energy systems, transportation electrification, smart grid, and cybersecurity of power systems (Homepage: www.HadiAmini.com).

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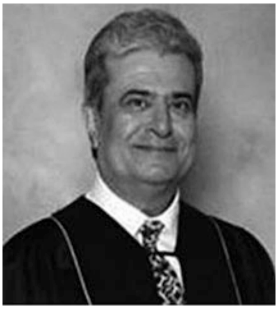
S. S. Iyengar is a Distinguished University Professor, Distinguished Ryder professor, and Director of the School of Computing and Information sciences and is the founding Director of the Discovery Lab at Florida International University. He has published over 600 research papers and has authored/coauthored/edited 24 books published by MIT Press, John Wiley & Sons, Prentice Hall, CRC Press, and Springer. He is a member of the European Academy of Sciences, a Fellow of IEEE, a Fellow of ACM, a Fellow of AAAS, a Fellow of NAI, a Fellow of AIMBE, a Fellow of the Society of Design and Process Program (SPDS), and a Fellow of the Institution of Engineers (FIE). He was awarded a Distinguished Alumnus Award of the Indian Institute of Science, Bangalore, and was awarded the IEEE Computer Society Technical Achievement Award for the contributions to sensor fusion algorithms and parallel algorithms. He is also a senior Fulbright distinguished specialist award winner. He is a Golden Core member of the IEEE-CS, and he has received a Lifetime Achievement Award conferred by the International Society of Agile Manufacturing (ISAM). Prof. Iyengar is TIMES NETWORK NRI award winner in 2017. He has served on many National Science Boards such as NIH—National Library of Medicine in Bioinformatics, National Science Foundation review panel, NASA Space Science, Department of Homeland Security, Office of Naval Security, and many others. He is also the founding editor of the *International Journal of Distributed Sensor Networks*. He has been the editor for many IEEE journals. He is presently the editor of *ACM Computing Surveys* and other journals. His work has been featured on the cover of the National Science Foundation's breakthrough technologies in both 2014 and again in 2016.

Panos M. Pardalos is a Distinguished Professor and the Paul and Heidi Brown Preeminent Professor in the Departments of Industrial and Systems Engineering at the University of Florida, and a world-renowned leader in Global Optimization, Mathematical Modeling, and Data Sciences. He is a Fellow of AAAS, AIMBE, and INFORMS and was awarded the 2013 Constantin Caratheodory Prize of the International Society of Global Optimization. In addition, Dr. Pardalos has been awarded the 2013 EURO Gold Medal prize bestowed by the Association for European Operational Research Societies. This medal is the preeminent European award given to Operations Research (OR) professionals for "scientific contributions that stand the test of time." Dr. Pardalos is also a Member of the New York Academy of Sciences, the Lithuanian Academy of Sciences, the Royal Academy of Spain, and the National Academy of Sciences of Ukraine. He is the founding editor of *Optimization Letters*, *Energy Systems*, and co-founder of the *International Journal of Global Optimization*. He has published over 600 papers, edited/authored over 200 books, and organized over 80 conferences. He has about 56,000 citations on his work, an H-index of 95, an i10-index of 575 (Google Scholar), and has graduated 62 Ph.D. students so far.

Frede Blaabjerg is a professor at Aalborg University, Department of Energy Technology. After graduation he was at ABB Scandia for 1 year and then he got the opportunity to become a Ph.D. student at the Institute of Energy Technology (now department), Aalborg University, 1988–1992, quickly taking larger responsibilities in the department and became a full professor in Power Electronics and Drives at the Institute of Energy Technology in 1998. Between 2000 and 2006, Frede Blaabjerg held positions such as Program Research Leader in Control of wind turbines at the Risoe (2000–2002); in 2000 and 2002 he was a visiting professor at the University of Padova, Italy, and Curtin University of Technology, Perth, Australia, respectively. From 2006 to 2010 he was the Dean of the Faculties of Engineering, Science and Medicine at Aalborg University, Denmark, an organization with a budget in 2010 at around 1300 Mio DKK. He decided to return to research in 2010. The Danish industry asked him to help to establish research in power electronics reliability, and he was able to initiate the Center of Reliable and Efficient Power Electronics (www.corpe.et.aau.dk), which today has more than ten companies involved in the research as well as many international collaborators. He attracted also an ERC advanced grant called Harmony (www.harmony.et.aau.dk) in 2012. Today, he is Villum investigator. A number of minor projects are also a part of the project portfolio today and his team has 30–40 people (dependent on number of guest and active projects). He became a visiting professor with Zhejiang University in 2009, and he is guest professor at Harbin Institute of Technology, Shandong University, and Shanghai Maritime University. He has published more than 1000 scientific papers. Conference papers are used as a platform to train PhDs and postdocs and then publish the best results in journals. However, many conference papers have received awards. Today more than 500 papers are published in journals. He has published ten edited books in power electronics and four monographs. The citations are quite high in the field of electrical engineering with +33000 in Web of Science (h-index 87); +51000 in Scopus (h-index 107), and +81000 in Google Scholar (h-index 132). In 2014, 2015, 2016, 2017, and 2018 he was among the most 250 cited in Engineering (Thomson Reuter). He is honoris causa at Politehnica of Timisoara, Romania, and Tallinn Technical University, Estonia. In 2019 and 2020 he will be President of IEEE Power Electronics Society.



Asad M. Madni served as President, COO, and CTO of BEI Technologies Inc. from 1992 until his retirement in 2006. He led the development and commercialization of intelligent micro-sensors, systems, and instrumentation for which he has received worldwide acclaim. Prior to BEI he was with Systron Donner Corporation for 18 years in senior technical and executive positions, eventually as Chairman, President, and CEO. Here, he made seminal and pioneering contributions in the development of RF and Microwave Systems and Instrumentation, which significantly enhanced the capabilities of the US Tri-Services and allies. He is currently an Independent Consultant, Distinguished Adjunct Professor/Distinguished Scientist at UCLA ECE Department, Faculty Fellow at the UCLA Institute of Transportation Studies, Adjunct Professor at Ryerson University, and Executive Managing Director and CTO of Crocker Capital. He received an A.A.S. from RCA Institutes Inc., B.S. and M.S. from the University of California Los Angeles (UCLA), Ph.D. from California Coast University, S.E. from MIT Sloan School of Management, D.Sc. (h.c.) from Ryerson University, D.Eng. (h.c.) from Technical University of Crete, Sc.D. (h.c.) from California State University and California State University Northridge, and Ph.D. degrees (h.c.) from Universiti Kebangsaan Malaysia and from National Chiao Tung University, Taiwan. He is also a graduate of the Engineering Management Program at the California Institute of Technology, the Executive Institute and Director's College at Stanford University, and the Program on Negotiation for Senior Executives and Promoting Innovation and Organizational Change at Harvard University. He is credited with over 180 refereed publications, 69 issued or pending patents, and is the recipient of numerous national and international honors and awards including IEEE Frederik Philips Medal, UCSD Gordon Medal for Engineering Leadership, Mahatma Gandhi Pravasi Samman Gold Medal, Ellis Island Medal of Honor, IET (UK) J.J.Thomson Medal, IEEE Millennium Medal, TCI College Marconi Medal, UCLA Professional Achievement Medal, UCLA Engineering Alumnus of the Year Award, UCLA Engineering Lifetime Contribution Award, UCLA EE Distinguished Alumni Award, IEEE-HKN Vladimir Karapetoff Award, IEEE AESS Pioneer Award, IEEE HKN Eminent Member Award, IEEE IMS Career Excellence Award, and Tau Beta Pi Distinguished Alumni Award. In 2011 he was elected to the US National Academy of Engineering "for contributions to development and commercialization of sensors and systems for aerospace and automotive safety." In 2014 he was elected a Fellow of the National Academy of Inventors "for demonstrating a highly prolific spirit of innovation in creating or facilitating outstanding inventions that have made a tangible impact on quality of life, economic development, and the welfare of society." He is a Fellow/Eminent Engineer of 15 of the world's most prestigious professional academies and societies and has been awarded six honorary professorships.

Chapter 1
Interdependent Networks from Societal Perspective: MITS (Multi-Context Influence Tracking on Social Network)

Ramesh Baral, S. S. Iyengar, and Asad M. Madni

Introduction

Overview

The real-world system can be represented in terms of multiple complex and semantically coherent networks. The networks have some correlation among each other and complement each other's functionality. Such correlated networks are termed as interdependent networks. The notion of a smart city can be represented as an integration of several interdependent networks that can facilitate secured and efficient management of a city's assets, such as transportation, power grids, water supply channel, distributed sensor networks, societal networks, and other services. In this chapter, we introduce the societal perspective of interdependent networks, where the users' and locations' networks are exploited to track the influential user and location nodes.

The task of identifying and tracking influential nodes in the ever-growing information networks is crucial to real-world problems that require information propagation (e.g., viral marketing). The exploitation of social networks for influential node detection has been quite popular in the last decade. However, most of the studies have focused on networks with homogeneous nodes (e.g., user-user nodes),

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and have also ignored the impact of relevant contexts. The information networks have heterogeneous entities that are interconnected and complement each other's functionality. Hence, the classical techniques popular in modeling the spreading of epidemics in simple networks may not be efficient.

We propose a model called MITS (**M**ulti-context **I**nfluence **T**racking on **S**ocial Network) that represents the contextual exploitation of heterogeneous nodes (i.e., user-location nodes in Location-based Social Networks (LBSN)), formulates the locality-aware spatial-socio-temporal influence tracking problem using Brooks-Iyengar hybrid algorithm, and uses the geo-tagged check-in data to identify and track the locality influence. The empirical evaluation of the proposed model on two real-world datasets, using the Susceptible-Infected-Recovered (SIR) epidemic technique, coverage, and ratio of affection metrics demonstrates a significant performance gain (e.g., 10–85% on coverage and 14–39% on ratio of affection) of the proposed model against other popular techniques, such as degree centrality, betweenness centrality, closeness centrality, and PageRank.

Background and Motivation

The notion of a smart city can be represented using different complex interdependent networks. The first volume of this book [1] presents the investigation of complex and interdependent networks from both theoretical and practical perspectives, including the networked control systems, graphics processing unit, smart cities, dynamic social networks, electrified transportation networks, and sustainable campus development. There are many interesting real-world examples of interdependent networks, such as power grid, transportation network, water supply channel, communication network, societal network, the Internet and the World Wide Web, points-of-interest network, phone call network, actor's collaboration network, co-authorship collaboration and citation network, genetic, metabolic, and protein network, and many other relevant services [2–6]. An optimal and secured operation of resources among these interdependent networks is needed to fulfill the goal of a smart city. The flow of information among these interdependent networks can play significant role on our daily life, for instance, the real-time tracking of traffic can be propagated on social networks, helping travelers to select alternate routes, real-time tracking of weather from distributed sensors can help residents to plan their outdoor activities, tracking of information flow on social networks can help to identify current trend and influential activities (e.g., trends on disasters, such as hurricane, trends on disease spread, trends on political activities, etc.), the contextual analysis of distributed sensor data can help in movement of disabled individuals [7], social network analysis (e.g., social interaction of factory workers [8], phone calls [9], communication networks on Internet [10], citation network [11]), interdependent power and transportation networks [12], metabolic networks (e.g., understanding cancer cell growth [13]), brain networks (e.g., study of brain dynamics [14–16]), community detection [17], island evolution in large epitaxial systems [18], and so forth. Despite the usefulness, the structural complexity, dynamic network and complexity, diverse nodes and connection are the major challenges behind the study of complex networks [19]. The interdependent networks are functionally correlated and the failure of a part of one network can have adverse impact on another. The exploration of their failures (e.g., blackouts resulting from cascading failures of power grid, communication systems, and financial transactions) and robustness are also of great interest [20–30] in the research community.

The graph theory [31–33] is the classical framework applied to solve many problems related to complex networks. The shortest path between nodes, clustering index, the degree centrality [34, 35], betweenness centrality [36, 37], closeness centrality [38], and k-shell decomposition methods [39] account for local or global topological network structures (see section "Related Research" for detail). The exploration of social interactions started in the early 90s [40]. The exploration of student's choice on the companions [41] and social interactions between factory workers [8] are some of the early studies in social network analysis. The concept of random graphs (randomly selecting a node to form a cluster with already selected nodes) to analyze the topology of graphs [42] was used to model gene networks, ecosystems of disease and computer viruses [43, 44]. The scale-free networks (modeling the connectedness of nodes) are believed to be robust to random failures [45], and were explored for therapeutic drugs [46] and metabolic networks [46, 47]. The comprehensive studies from Boccaletti et al. [6] and Newman [48] present different phases of development of complex and interdependent networks.

One of the interesting real-world applications of complex network is the social network (e.g., Facebook,[1] Twitter,[2] Yelp,[3] etc.). The social networks can be exploited for different practical problems (e.g., friendship recommendation, tag prediction, opinion-sentiment analysis, location recommendation, item recommendation, etc.). This chapter focuses on identifying and tracking of influential nodes in LBSN. The task of influential item detection has been a popular research problem in the past decade. The influence maximization problem in a graph $G=\langle U,V \rangle$ selects a set of seed nodes in such a way that the expected spread of information (i.e., influence spreads) in the graph is maximized [49]. There are many real-world problems that exploit influence detection techniques for their business needs. As an example, in a marketing business, one can identify few influential customers and distribute promotional items to them. The strategy is to select a smallest possible subset of customers who can positively influence (e.g., via word-of-mouth effect) their networks towards the consumption of the promotional items, and propagate the influence on the network (i.e., viral marketing) to an expected scale.

An interesting example is the exploitation of social networks to identify the influential candidate in US presidential election. For the 2016 election, several models predicted ~80% winning chances of Hillary Clinton. Most of those studies

[1] www.facebook.com.

[2] www.twitter.com.

[3] www.yelp.com.

exploited user polls, activities and posts from different social networks to capture the correlation between different parameters and to formulate the influence propagation for both candidates, and predicted the winning likelihood using their influence scores. As the correlation need not necessarily imply causation, the actual result was opposite of the predictions. This implies that those models should have been impacted by some noisy information from the social networks. For instance, for any two users, having posts in support of one candidate need not necessarily indicate their voting decision. A contextual exploitation of information on social networks is essential to model the influential parameters and to handle the noisy information.

The influential sensor measure to project the correct measure via different sensor fusion techniques [50–52] is another interesting application. The influence maximization can also be exploited on Point-of-Interest (POI) domain by exploiting the check-in preferences (e.g., likes/dislikes, tags, emoticons, reviews, stars/ratings, etc.) shared on LBSN. The sharing of positive experience can induce the linked users towards the consumption of relevant items. Intuitively, this gives us the formulation of influence tracking and influencer identification in LBSN, which can be modeled to maximize the number of potential visitors to a given POI. In this paper, we study navigation patterns of users based on LBSN data to determine influential locations (interchangeably termed as POI in this paper).

Figures 1.1 and 1.2 illustrate the spatial influence of a POI and user to the nearby POIs. As shown in Fig. 1.1, the spatial influence of the *Statue of Liberty* is high to

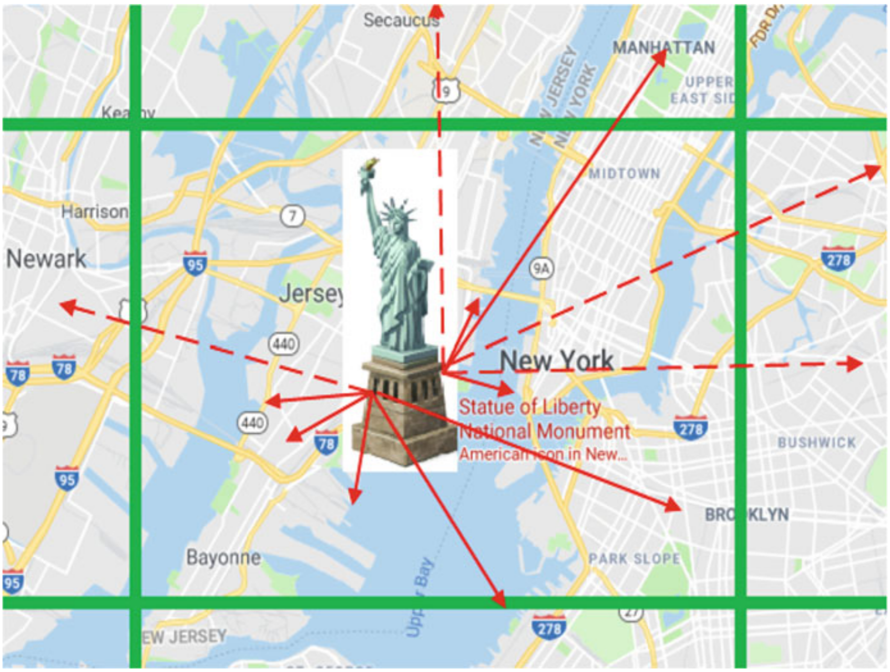


Fig. 1.1 POI grid distance influence

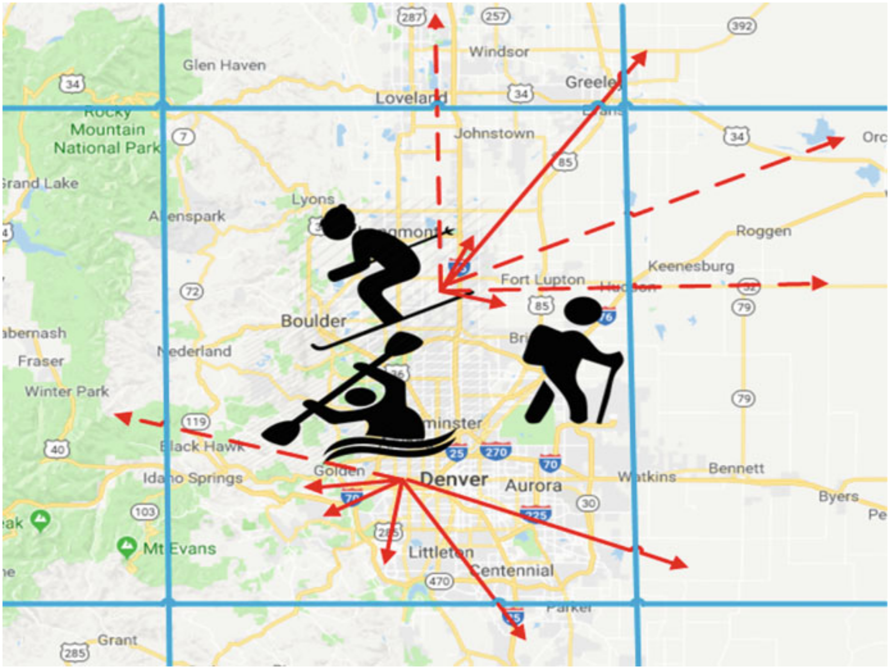


Fig. 1.2 User grid distance influence

the nearby POIs. This implies most of the users who visit the *Statue of Liberty* have high chance of visiting the nearby POIs. The influence decreases with the distance, i.e. the farther POIs have less spatial influence from it. Figure 1.2 shows the user influence to the nearby POIs. Whenever a user has some activity on a region or a POI, the nearby POIs have high chance of being visited by the user. The category of POI, time of a day, and social relation of user also play crucial role in modeling the influence of user and POIs.

There are many interesting studies that are focused on finding influential users [53], popular events [54], or popular locations [55], but our study is focused on identifying the sets of users and POIs that have high spatial impact on other POIs. With the growing usage of smart-phones and social networks, exploitation of spatial information from mobile customers is essential in identifying the spatially influential entities, and tracking their evolution over time.

The research formulation of influence maximization was first described by Domingos and Richardson [56]. It was first formulated as a discrete optimization problem by Kempe et al. [49], who also proved it as an NP-hard problem, and proposed a greedy optimization algorithm. However, the greedy algorithm executes a Monte Carlo simulation to approximate the solution of influenced set size, and is computationally complex. The classical techniques, such as degree centrality, betweenness centrality, closeness centrality, and k-shell decomposition, are quite popular in identifying influential nodes in a network. Some of the classical techniques, such as the degree centrality [34, 35], betweenness centrality [36, 37], closeness centrality [38], and k-shell decomposition methods [39], account for local or global topological network structures, with some limitations. These techniques mostly shine with large networks, are unable to handle small propagation probability as they can identify only few central and overlapping nodes as the influential nodes of the network, do not handle spreading and propagation probability, and are difficult to model on multi-context and heterogeneous networks.

Furthermore, the existing studies focused on location information in influence maximization only, exploited location as a simple user property, and did not analyze the contextually dynamic user mobility behaviors. In this paper, we incorporate multiple contexts (e.g., categorical, social, spatial, and temporal) of user check-ins to define the influence scores due to check-ins, and influence scores due to spatial impact. Such scores are then exploited via optimal region technique utilizing the Brooks-Iyengar algorithm [57] to find a set of users and POI influencers on location grids. The optimal region technique also helps to filter out the noisy nodes from the network. An extensive evaluation on two real-world datasets demonstrates the efficiency of our proposed model when compared to the several classical methods, such as degree centrality, closeness centrality, betweenness centrality, and PageRank-based methods. The core contributions of our study are: (1) it formulates the location promotion problem as influential user and influential POI tracking problem, (2) it presents a multi-context influence formulation by incorporating the social, temporal, categorical, and spatial attributes in the influence tracking task, and exploits an optimal region technique to find the influencing nodes in a network, and (3) it extensively evaluates the proposed model with two real-world datasets.

Related Research

The ***centrality measure*** technique is one of the classical techniques and is focused on ranking nodes in networks. A simple centrality measure is the *degree centrality* (DC) [58] of a node and is defined as the number of nearest neighbors. This technique assumes that a node with larger degree is likely to have higher influence than a node with smaller degree. However, in some cases, this method fails to identify influential nodes, since it considers only very limited information. The *closeness centrality* (CC) [38] measure of a node v is defined as the reciprocal of the sum of geodesic distances to all other nodes V in the network: $C_c(v) = \frac{1}{\sum\limits_{v' \in (V-v)} d_G(v, v')}$, where $d_G(v, v')$ is the geodesic distance between v and v'. Closeness gives a measure of how long it will spread information from a given node to other reachable nodes in the network.

The *betweenness centrality* (BC) [59] is a centrality measure of a node and is defined as the fraction of shortest paths between node pairs that pass through the node of interest. It gives a measure of the influence of a node over the information spread through the network or the expected load of a node in a transportation network. For a network G= (V,E) with n = | V | nodes and m=| E | edges, the *betweenness centrality* of a node v is defined as $C_B(v) = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$, where σ_{st} is the number of shortest paths between nodes s and t, and $\sigma_{st}(v)$ denotes the number of shortest paths between s and t which pass through node v. Some studies [60–63] have shown that the betweenness and closeness centrality measures can better quantify the influence of a node, but have higher computational complexity. They also claimed that the centralities based on PageRank [61] are even more relevant but more time-consuming. Though these classical techniques may work for simple networks, they have no provision for information rich networks, such as LBSN that contains multiple contexts.

The ***k-shell decomposition*** method is another popular approach and is implemented by repeatedly deleting the nodes with degree one, and then nodes with degree two, and so on. The first iteration of node deletion is repeated until all nodes' degrees are larger than one. All of these removed nodes are assigned to 1-shell. Then recursively all the nodes with degree of at most two are removed until all nodes' degrees are larger than two. The removed nodes are assigned to 2-shell. The process is repeated until all of the nodes are assigned to one of the shells [64]. In some cases, the centrality measures can have little effect on the range of the spreads and can have less impact than the strategically oriented nodes in the center of a network and with smaller degree. Some of the existing studies [39] have also shown that k-shell method can outperform the degree centrality index in many real networks.

The **Independent Cascade Model (ICM)** [49] exploits the propagation probability in a graph. Given an edge ⟨u,v⟩, and node *u* is active at time *t*, the propagation of edge ⟨u,v⟩ at time *t+1* is defined as p(u,v). The process starts with some seed nodes as active nodes and rest as inactive. The propagation is controlled using some measures, such as node degrees [49], and the process is repeated until some node gets activated. Barbieri et al. [65] extended a similar concept and incorporated topic-based information propagation. Zhu et al. [66] proposed the Gaussian-based and distance-based user mobility models, to formulate the location aware propagation probability for location promotion. Their model focused on finding seed users that can influence check-ins to a given location. They did not focus on finding the influential locations.

Wang et al. [67] proposed a community-based greedy algorithm to find the influential nodes. They extended the basic independent cascade model and exploited the dynamic programming and information diffusion among the nodes to split them into small communities. Lu et al. [60] proposed a random-walk-based model called LeaderRank and identified influencers in social networks. It outperformed the PageRank [61] algorithm in identifying the influential nodes for opinion spreading and protecting from the spammers' attacks. Such ranking-based models may not be efficient for undirected networks which will degenerate the degree centrality. Chen et al. [68] proposed a local centrality measure that used the nearest and next nearest neighbors. The local centrality $C_L(v)$ of a node v was defined as: $Q(u) = \sum_{w \in \tau(u)} N(w)$; $C_L(v) = \sum_{u \in \tau(v)} Q(u)$, where $\tau(u)$ is the set of nearest neighbors of node u and $N(w)$ is the number of the nearest and the next nearest neighbors of node w. Zhang et al. [69] used the information transfer probability between any pair of nodes and the k-medoid clustering algorithm for identifying influential nodes in complex networks with community structure.

Li et al. [70] proposed an in-degree based greedy model that focused on finding set of influencing users for a query region and the location of users. However, they did not focus on the mobility of users. The in-degree technique also cannot capture the set of influential nodes that have smaller degrees but yet contextually relevant for the target domain. Zhu et al. [55] focused on finding the set of influential users for location promotion.

The exploitation of k-truss model from Malliaros et al. [71] also demonstrated better performance against the degree centrality measures. Recently, Wang et al. [72] proposed a multi-attribute ranking technique by exploiting the neighborhood's effect on the influence capability of a node. Wang et al. [73] proposed a fast ranking method to evaluate the influence capability of nodes using a k-shell iteration factor. They defined a relation to incorporate the degree and number of neighbors of a node to represent the influence of a node. The famous k-shell method treats nodes based on the degree at an instant and is not concerned about the original degree of the nodes and also does not address the closeness of a node to the core nodes and the location of nodes in a network.

We can see that most of the existing studies focused on identifying homogeneous influential nodes in different networks. Furthermore, exploitation of multiple contexts for heterogeneous influential node detection is less explored. Our study has the following uniqueness in comparison with the existing studies: (1) it formulates the influence identification problem as a heterogeneous graph (i.e., user-POI graph) and identifies heterogeneous nodes (e.g., user and POI) as influential nodes in a network, (2) it exploits multiple contexts and defines each node with an interval of two different types of scores (i.e., score due to check-in influence and score due to spatial influence). This not only facilitates the incorporation of spatial and check-in popularity, but also handles the trade-off between the spatial and check-in influences, (3) it exploits the optimal region technique based on Brooks-Iyengar hybrid algorithm [57], and eliminates the noisy nodes that have small overlap with other nodes, and (4) it presents a simple and efficient technique for locality-based (i.e., influential nodes on different localities) influence maximization in location-based network.

Methodology

Many of the existing studies have defined a single composite score to identify the influential nodes in social networks. The LBSN is a special case that has many implicit factors (e.g, check-in time, location category, social relation, distance to a location, utility of a location, and so on) that can play a crucial role in identification of influential nodes. The Point-of-Interest (POI) domain can exploit such implicit

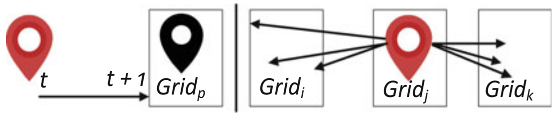


Fig. 1.3 Left part shows the successive check-ins for POI-checkin influence and the right part shows the spatial influence of a POI to other POIs

factors and the explicit factors (e.g., the check-in, ratings, reviews, etc.) to define the contextual scores of a user and POI and identify the contextually influential nodes in the LBSN. Figure 1.3 illustrates the impact of visits and spatial impact on check-ins. The left part of the figure shows that if a POI visited at time t has influence on another POI, then it is most likely to be visited at time $t+1$. As an example, if the *Statue of Liberty* has visit influence on some POIs, then those POIs will be visited by the users after they visit the *Statue of Liberty*. The right part of figure shows the spatial impact. The spatial impact of POI implies that the impact of a POI to nearby places is higher than that of the farther places. For instance, the influence of the *Statue of Liberty* is higher around New York city and New Jersey city and the influence is less on farther cities.

We divide all the locations into L uniform geographical grids (i.e., $\mathbb{L} = \{g_1, g_2, \ldots, g_L\}$) as in [74]. We define the following two types of scores of a user and a POI on a grid (g_l) based on the check-in frequencies and the spatio-temporal influences:

1. POI-grid visit influence (v_s^l): It is the score of a POI to a grid due to the check-in behavior of its visitors (see Fig. 1.3 left part). The visit influence of a POI i to a grid g_l is the number of check-ins from the visitors of i to the grid g_l and is defined as:

$$y(v)_i^l = \sum_{l' \in g_l} \sum_{t=1}^{T} \sum_{t'>t}^{T} \frac{|\ V_{i,l',t}\ |}{|\ V_{l',t'}\ |}, \tag{1.1}$$

   where the term $|\ V_{i,l',t}\ |$ is the frequency of check-ins to l' at time t and succeeding the ones to POI i, and $|\ V_{l',t'}\ |$ is the number of visits made to the POI l' at time t'.
2. User-grid visit influence (v_s^u): It is the score of a user to a grid due to her check-in behavior. The visit influence of a user u to a grid g_l is defined in terms of the number of check-ins from her friends that succeed her check-ins to the common places, and is defined as:

$$x(v)_u^l = \sum_{l' \in g_l} \sum_{t=1}^{T} \left\{ \alpha \times \frac{|\ V_{u,l',t}\ |}{|\ V_{l',t}\ |} + (1-\alpha) \times \sum_{t'>t}^{T} \sum_{u' \in u_f} \frac{|\ V_{u',l',t'}\ |}{|\ V_{l',t'}\ |} \right\}, \tag{1.2}$$

   where $|\ V_{u,l',t}\ |$ is the frequency of check-ins made by user u to POI l' at time t, u_f is the set of friends of u, and α is a constant tuning factor.

3. POI-grid distance influence (y_i^l): It is the influence score of a POI i to a grid g_l due to the spatial impact (see Fig. 1.3 right part). We define a 2-D kernel density estimation to represent the influence of a POI to a grid:

$$y_i^l = \frac{1}{\sigma} K\left(\frac{d(i,l)}{\sigma}\right), \tag{1.3}$$

where $d(i,l)$ is the geographical distance between the POI i and the center of the grid g_l, $K(.)$ is a 2-D kernel density estimation, and σ is the standard deviation of the distances between the locations in the grid g_l. We further extend this relation to incorporate the categorical and temporal contexts, and is defined as:

$$y_i^{lt} = y_i^l + \frac{1}{\mid g_l \mid} \sum_{l' \in g_l} (C\alpha y_i^{l'} + \mathcal{T}\beta y_i^{l'}), \tag{1.4}$$

where C is the indicator variable to check if l' is of same category as l, $\mathcal{T}$ is the indicator variable to check if l and l' have common check-in time, and α, β are constants such that $\alpha+\beta=1$.
4. User-grid distance influence (x_i^{lt}): It is the influence score of a user to a grid due to spatial and social contexts. We use a 2-D kernel density estimation to represent the influence of a user at location i to a grid g_l:

$$\begin{aligned} x_i^{lt} &= \psi \times \frac{1}{\mid V_{ut} \mid} \sum_{l \in \mathbb{L}_u} \frac{\eta_u^{lt}}{\sigma} K\left(\frac{d(i,l)}{\sigma}\right) \\ &+ (1-\psi) \times \sum_{u' \in u_f} \frac{1}{\mid V_{u't} \mid} \sum_{l' \in \mathbb{L}_{u'}} \frac{\eta_u^{l't}}{\sigma} K\left(\frac{d(i,l')}{\sigma'}\right), \end{aligned} \tag{1.5}$$

where $\mid V_{ut} \mid$ is the number of check-ins made by user u at time t, $\mathbb{L}_u$ is the set of locations visited by user u to the grid g_l, η_u^{lt} is the number of check-ins made by user u to the grid g_l at time t, σ is the standard deviation of the distances between the locations in the grid g_l, and ψ is a constant.

These scores are normalized and each user u is represented by a pair of scores $(\min(v_s^u, x_l^u), \max(v_s^u, x_l^u))$ for each grid/region g_l. A similar approach is used to define a pair of scores $(\min(v_s^l, y_l^i), \max(v_s^l, y_l^i))$ for each POI l for each grid g_l. Such pair of scores are defined for each and every user and each and every POIs for a given region. We then identify the most overlapping min-max pairs. This approach provides two major benefits, first the computation cost is lowered, second the noisy nodes with very high or very low min-max scores get filtered out easily in the early steps of the process. Besides these, the model is simple and can be easily adopted to other relevant problems.

The high level overview of the proposed model is illustrated in Fig. 1.4. The core steps of the model are as follows:

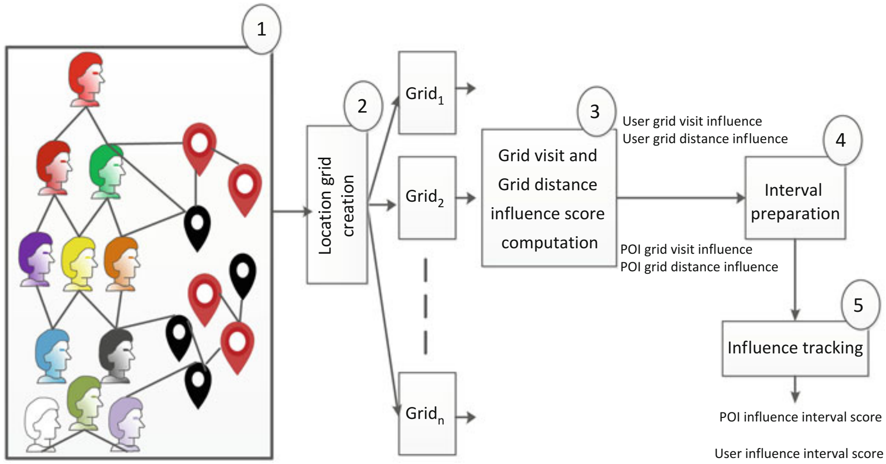


Fig. 1.4 High level overview of MITS

1. The first step is to identify the target network for which the influential nodes are to be identified. The LBSN provides many contexts that can be exploited to identify the influential nodes. The LBSN can be represented as a graph that contains user and POI nodes. The user–user edges exist if the two users have social link (e.g., friendship) between them. The user–POI edges exist if the user has a check-in to the POI. The POI–POI edge exists if the POIs have same category or have distances within some threshold. There are many other contexts, such as check-in time, location category, etc.
2. Location grid creation: It is difficult to model the contextual influence in the whole network. Inspired from [74], we divide all the locations into grids/regions of uniform areas. Each location grid contains a set of locations in the region.
3. Grid visit and grid distance score computation: For each user and POI, we compute two different scores for each region. One of the scores is due to the impact of visit and the another is due to the impact of distance. We use Eqs. (1.1)–(1.5) to compute these scores for each user and POI nodes.
4. Interval preparation: For each region, we need to find a measure that represents the influence score of the region. As the social network contains lot of noise, it is difficult to predict the exact score for the influential nodes, so we project an interval of score. We normalize the scores computed in the previous step and transform the scores into some buckets or intervals (e.g., {[0, 10], [11, 20], . . ., [91, 100]}).
5. Influence tracking: We extend the Brooks-Iyengar algorithm (see Algorithm 1) to compute the interval score that represents a projection of score for a region. If the score of a node overlaps with the projected interval, then the node is taken as an influential node. The influence tracking process is independently performed for user nodes and POI nodes in each region.

Algorithm 1 provides the detailed steps of the proposed model.

Algorithm 1 Influence tracking

1: **INPUT: (U, L, G$_i$, N, k)**, **U** is the set of all users, **L** is the set of all POIs, **G**$_i$ is the i^{th} geographical region, **N** is the number of users, **k** is the number of influencers to be identified
2: **OUTPUT:** $\mathcal{I}_i$, a list of influencer nodes for region G$_i$
3: get the normalized intervals of scores of all user-item nodes
4: initialize empty lists $\mathcal{I}_i$ and $\mathcal{A}_i$ to hold the influencer nodes and active nodes respectively
5: sort the user nodes by their minimum scores
6: **for** each user node u_i from step 5 **do**
7:     **if** $u_i.min$ has already been traversed but $u_i.max$ has not been traversed **then**
8:         mark this node as active, add it to $\mathcal{A}_i$
9:     **end if**
10:     /**remove the first user node whose maximum value is less than or equal to current minimum value**/
11:     **if** $\mathcal{A}_i$.size > **k and** $\mathcal{A}_i[0].max < u_i.min$ **then**
12:         remove $\mathcal{A}_i[0]$ /**remove the first non-overlapping node**/
13:     **end if**
14:     **if** $\mathcal{A}_i$.size $\geq$ **k then**
15:         add the nodes from $\mathcal{A}_i$ to $\mathcal{I}_i$, if not already present
16:     **end if**
17: **end for**
18: sort the **k** or more min-max pairs in $\mathcal{I}_i$, and use its lowest min score and highest max score to define the lower and upper influence bound of G$_i$
19: For the **k** min-max pairs in $\mathcal{I}_i = \langle (l_i^1, h_i^1), (l_i^2, h_i^2), \ldots, (l_i^k, h_i^k) \rangle$, find a score $v_i = \frac{\sum_{n=1}^{k} \frac{(l_i^n + h_i^n) * w_i}{2}}{k}$, where w_i is the weight of the corresponding interval of min-max scores in $\mathcal{I}_i$. The score v_i represents the threshold influence score of the region, and the pair (l_i^1, h_i^k) represents the interval estimate of the influence score.

Explanation of Algorithm 1 The step 3 uses Eqs. (1.1)–(1.5) to get the min-max pair scores and normalizes them. In step 4, we initialize lists to hold the active and influencer nodes. In step 5, we sort the min-max pairs. The step 6 traverses the sorted nodes. The step 7 keeps track of the traversed pairs and marks the nodes as active if their min score is already traversed and max score is not traversed. This is useful to keep track of the overlapping nodes. In step 11, the first non-overlapping pair is removed from the current active list. As we keep on adding new nodes to the active list $\mathcal{A}_i$, we check if the first node overlaps with the current node or not. There is an overlap if the pair of scores of the two nodes intersect. The higher the overlap of a pair of score, the higher the chance of it being an influential node. If there is no overlap, then the node is removed from the active nodes list. If the node was not an outlier, then it should be from an interval with high weight.

Removing the earlier entries of an interval will not be a problem because there will still be other entries from this interval with high min-max value. If the node was an outlier, then there will be only few or none entries left from this interval, hence removing the first entries with smaller max score should not be a problem.

The step 14 accumulates the active nodes into the influencers list $\mathcal{I}_i$. The step 18 uses the k or more min-max pairs stored in $\mathcal{I}_i$ list to find the lowest min and highest max score to define a low-high bound for the potential influencer nodes. This bound gives the estimated measure of the influence score interval, i.e. any node having the score overlapping with this interval is considered as a potential influencer. If we want to ensure that only top-k min-max pairs are included in the low-high bound, we can get the last k entries from the $\mathcal{I}_i$.

In step 19, we use the min-max pairs and their weight/frequency from $\mathcal{I}_i$ to find the average value of the influence score. This average value can be used as an aggregated score of influencing nodes and can be used to the scenarios that generate a single composite score. If a node's composite score falls within some range of this aggregate score, then the node can be taken as influential node. As the user and POI nodes can have different measure for the influence scores, the Algorithm 1 is independently executed for user and POI nodes.

Complexity Analysis

For each region, the sorting step takes $O(NlogN)$, where N is the number of min-max pairs. Algorithm 1 has an additional step that removes the active nodes whose max score is less than the min score of the currently processed node. The extra step incurs a cost of removing the first item from the active list, and depending on the data structure used, the cost can range from $O(\log N)$ in the best case to $O(N)$ in worst case.

Evaluation

This section presents the dataset, evaluation metrics, evaluation baselines, experimental settings, and results and discussions.

Dataset

We evaluate our proposed model MITS with two real-world datasets Weeplace [4] and Gowalla [75]. The statistics of the datasets is shown in Table 1.1. The datasets are well organized and have all the attributes relevant to our model.

[4] http://www.yongliu.org/datasets/.

Table 1.1 Statistics of the datasets

Dataset	Check-ins	Users	Venues	Links	Location categories
Gowalla	36,001,959	319,063	2,844,076	337,545	629
Weeplace	7,658,368	15,799	971,309	59,970	96

Evaluation Metrics

We used the following evaluation metrics to evaluate the performance of the proposed model:

1. Coverage: It measures the fraction of check-ins on a region that is induced due to the influencing user and influencing POI. We find the fraction of check-ins on test set that are done after the check-ins done on the influencing POIs. We also find the fraction of check-ins from their friends that are done after the check-ins done by the influencing users. The process is repeated for different time windows (e.g., $t = 2, 5, 10$). The coverage of a region G_l due to a user u is defined as: $\sum_{t}^{T}\sum_{t<t'}^{T}(\sum_{\substack{l'\in G_l\\ l'\in L_u\\ u'\in u_f}} \mid V_{u',l',t'} \mid / \mid V_{u,l',t} \mid)$. The coverage of G_l due to a POI l is defined as: $\sum_{t=1}^{T}\sum_{t'>t}^{T}(\sum_{l'\in G_l} \mid V_{l,l',t'} \mid / \mid V_{l',t} \mid)$.
2. Ratio of Affection (RA): For a user u, this measures the fraction of friends that followed the check-ins of u to a region G_l, and is defined as: $\sum_{\substack{l'\in G_l\\ l'\in L_u}}(\sum_{u'\in u_f} \mid I(V_{u',l'}) \mid / \mid u_f \mid)$, where $I(.)$ is an indicator function. For a POI i, RA measures the fraction of POIs from a region that follow the check-ins made at i and is defined as: $\sum_{l'\in G_l}(\mid I(V_{i,l'}) \mid / \mid G_l \mid)$.
3. SIR (Susceptible, Infected, Recovered) model - In this model, for each region, a user-POI graph is built with the edges between user–user if there is a friendship relation, POI–user if there is a check-in by the user to the POI, and POI–POI edge if they are of same category and are within some threshold distance. The weight of the edges is determined by the fraction of common check-ins between two nodes. The influencing user and POI nodes are taken as the infected nodes and the spread propagation is simulated for each influencing node independently. Each influencing node undergoes 100 simulations and the average of all simulations is observed as the final measure. At a single instance of time, each infected node can infect one of the randomly selected neighbor nodes with probability (i.e., infection rate) equal to the edge weight. The infected nodes get recovered with probability λ (i.e., recovery rate) which is defined using the normalized weight of the neighbor nodes that were not infected in the original graph. The process is

repeated till there is no new infected node in the graph. We observe the average infected nodes for each region and the average recovered nodes after the network gets stable.

Evaluation Baselines

We used the following relevant models to evaluate the performance:

1. Degree Centrality: It uses the number of nearest neighbors of a node to compute the influence score. This model assumes that a node with larger degree has higher influence than a node with smaller degree (see section "Related Research" for detail).
2. Closeness Centrality: It measures the reciprocal of the sum of the geodesic distances to all other nodes in the network (see section "Related Research" for detail). The node with high closeness centrality measure is taken as the highly influential node.
3. Betweenness Centrality: It uses the fraction of shortest paths between node pairs that pass through the node of interest. The higher the fraction of shortest paths, the more influential is the node to the node pairs (see section "Related Research" for detail).
4. PageRank [61]: The PageRank algorithm is a very popular ranking algorithm. It uses the incoming and outgoing degrees of a node in a graph to compute the rank of the node. The rank of nodes are iteratively updated until the graph converges (i.e., there is minimal or no change in the rank of the nodes).

Experimental Settings

We divided all the locations into 1000 grids/regions with uniform area. Using the grid search technique, the parameter α in Eq. (1.2) was checked for {0.25, 0.5, 0.75}and the best result was found with the value of 0.5. Similarly, the values for parameters α and β were checked on the set {0.25, 0.5, 0.75}. The best result was achieved when $\alpha = 0.25$ and $\beta = 0.75$. For each of the identified influential nodes, we ran the SIR measure for 100 times and averaged the results. The SIR measure is observed for different time steps (i.e., $t = 2, 5, 10, 15, 20, 25, 30$).

Experimental Results and Discussion

We observe the evaluation of the following models: degree centrality, betweenness centrality, closeness centrality, PageRank [61], and our proposed model MITS.

Table 1.2 Coverage of different models on Weeplace and Gowalla dataset

	Models	POI coverage	User coverage
Weeplace	DC	0.2451	0.2241
	CC	0.3626	0.2377
	BC	0.3827	0.2403
	PageRank	0.4106	0.2551
	MITS	**0.4538**	**0.2802**
Gowalla	DC	0.2590	0.2361
	CC	0.3704	0.2405
	BC	0.3883	0.2493
	PageRank	0.4216	0.2627
	MITS	**0.4637**	**0.2928**

The bold values indicate statistically significant at 95% confidence level.

Table 1.3 Ratio of affection (RA) of different models on Weeplace and Gowalla dataset

	Models	POI RA	User RA
Weeplace	DC	0.2029	0.2035
	CC	0.2271	0.2276
	BC	0.2375	0.2337
	PageRank	0.2471	0.2401
	MITS	**0.2816**	**0.2618**
Gowalla	DC	0.2147	0.2161
	CC	0.2306	0.2306
	BC	0.2488	0.2391
	PageRank	0.2552	0.2517
	MITS	**0.2959**	**0.2704**

The bold values indicate statistically significant at 95% confidence level.

We divided all the locations into 1000 grids and observed the average values of coverage, RA, and SIR score on all of them. The coverage performance of different models on Weeplace and Gowalla dataset is shown in Table 1.2. The coverage of DC technique is least of all the models. The PageRank-based model outperformed all other models except our proposed model. In both datasets, MITS outperformed all the other models. This implies that the influence propagation of MITS reaches to broader set of nodes when compared to the relevant models.

The ratio of affection (RA) performance of different models on Weeplace and Gowalla dataset is shown in Table 1.3. MITS outperformed all the other models in terms of RA metric. This implies that the influential user nodes generated by MITS can impact the check-in of larger number of friend nodes in the same region. This also implies that the influential POI nodes generated by MITS can impact the higher number of successive check-ins to the POIs in the same region.

The SIR-based evaluation of different models is shown in Table 1.4. It shows the average number of infected nodes of all regions and all simulations for different time steps. We can see that the average number of infected nodes increases with time for all the models, until the network gets stable. The value for the DC model grows

Table 1.4 Average no. of infected nodes on different time steps

		Timesteps					
Dataset	Models	**2**	**5**	**10**	**15**	**20**	**25**
Weeplace	DC	127.26	172.38	205.17	258.71	433.51	430.25
	CC	141.81	191.50	227.20	271.92	451.61	429.01
	BC	159.20	199.29	235.39	274.99	469.28	418.30
	PageRank	165.91	218.20	242.29	291.69	485.97	410.29
	MITS	175.19	230.39	269.20	355.10	525.01	401.04
Gowalla	DC	257.46	1392.38	2281.67	2018.18	1544.51	1130.25
	CC	371.01	1471.91	2347.02	2002.20	1504.94	1115.66
	BC	402.79	1488.47	2388.83	1980.72	1483.81	1100.05
	PageRank	494.93	1527.37	2472.04	1959.37	1407.49	1063.69
	MITS	583.94	1605.70	2584.20	1920.84	1345.40	1017.47

slowest in comparison with other models. The value for our model grows faster and stabilizes faster. After gaining stability, there is no infection triggered and only recovery is triggered. We can see that our model achieves faster recovery because it gets stable earlier due to the high spreading capability and the recovery also starts earlier. As the Gowalla dataset is larger, it has more social connections, has more user and POI nodes on each grid/region, hence the average number of infected and recovered nodes is higher than that of Weeplace.

The trend on SIR technique-based influence spread over time or iteration is shown in Figs. 1.5 and 1.6. In the Weeplace dataset (see Fig. 1.5), all the models gain their maximum spread during time span 20. Though all of the models gain the maximum spread at this state, the number of nodes influenced varies among the models. The DC model has least number of influenced nodes. The MITS has highest number of influenced nodes. As the time or iteration increases, the influence spread stabilizes because no new nodes are infected and the infected nodes get recovered. We can see that the rate of recovery is fastest with MITS and is slowest with the DC model. The faster recovery leads to faster stability of the network. We can see that the PageRank and MITS models are almost stable after 35 iterations but the other models still have changes in the influence spread. Using the terms from SIR technique, we can say that the spread of infection and recovery are faster in MITS, when compared to the other models. This also implies a better influence propagation.

The influence spread trend on Gowalla dataset (see Fig. 1.6) has a spike during time span of 15 for all the models. Although all the models achieve the maximum spread at this time, the number of nodes influenced varies among the models. Similar to Weeplace dataset, the influence propagation of MITS model is better, when compared to the other models. As the Gowalla dataset is larger than Weeplace dataset, the number of influenced nodes is higher for all the models. In summary, the influence propagation of MITS is better than the relevant models when evaluated on both Weeplace and Gowalla dataset.

Fig. 1.5 Influence spread trend in Weeplace dataset

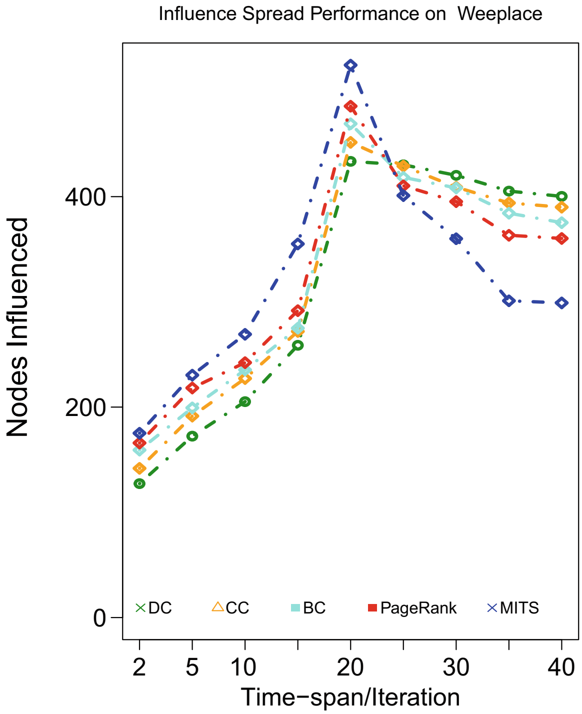
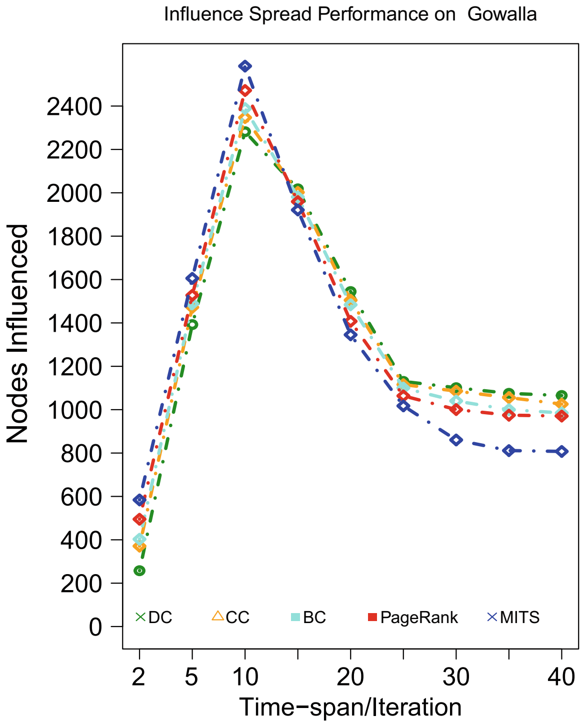


Fig. 1.6 Influence spread trend in Gowalla dataset



Conclusion and Future Work

We presented a societal perspective of complex interdependent networks by formulating the influence maximization problem on heterogeneous network (i.e., LBSN) using the optimal region maximization technique. We divided the locations into uniform grids and defined multi-context check-in based score and spatio-temporal scores for each user and POI nodes. The optimal region maximization technique was independently executed to find the influencing user and influencing POI nodes. The extensive evaluation on two real-world datasets and performance metrics, such as SIR, coverage, and ratio of affection demonstrates the efficiency of our proposed model over several popular techniques. As a future work, we would like to incorporate the opinion and sentiment of users expressed in the user reviews.

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References

1. Amini, M. H., Boroojeni, K. G., Iyengar, S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks: From theory to application*. Basel: Springer.
2. Cocchia, A. (2014). Smart and digital city: A systematic literature review. In *Smart city* (pp. 13–43). Basel: Springer.
3. Hall, R. E., Bowerman, B., Braverman, J., Taylor, J., Todosow, H., & Von Wimmersperg, U. (2000). *The Vision of a Smart City*, Brookhaven National Lab., Upton, NY (US). Technical Report.
4. Lombardi, P., Giordano, S., Farouh, H., & Yousef, W. (2012). Modelling the smart city performance. *Innovation: The European Journal of Social Science Research, 25*(2), 137–149.
5. Arasteh, H., Hosseinnezhad, V., Loia, V., Tommasetti, A., Troisi, O., Shafie-Khah, M., et al. (2016). Iot-based smart cities: a survey. In *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)* (pp. 1–6).New York: IEEE.
6. Boccaletti, S., Latora, V., Moreno, Y., Chavez, M., & Hwang, D.-U. (2006). Complex networks: Structure and dynamics. *Physics Reports, 424*(4–5), 175–308.
7. Gharani, P., & Karimi, H. A. (2017). Context-aware obstacle detection for navigation by visually impaired. *Image and Vision Computing, 64*, 103–115.
8. Scott, J., & Carrington, P. J. (2011). *The SAGE handbook of social network analysis*.Thousand Oaks: SAGE Publications.
9. Aiello, W., Chung, F., & Lu, L. (2002). Random evolution in massive graphs. In *Handbook of massive data sets* (pp. 97–122).New York: Springer.
10. Caldarelli, G., Coccetti, F., & De Los Rios, P. (2004). Preferential exchange: Strengthening connections in complex networks. *Physical Review E, 70*(2), p. 027102.
11. Price, D. J. D. S. (1965). Networks of scientific papers. *Science, 30*, 510–515.
12. Amini, M. H., & Karabasoglu, O. (2018). Optimal operation of interdependent power systems and electrified transportation networks. *Energies, 11*(1), 196.
13. Vogelstein, B., Lane, D., & Levine, A. J. (2000). Surfing the p53 network. *Nature, 408*(6810), 307.
14. Sompolinsky, H., Crisanti, A., & Sommers, H.-J. (1988). Chaos in random neural networks. *Physical Review Letters, 61*(3), 259.

15. Minai, A. A., & Levy, W. B. (1993). The dynamics of sparse random networks. *Biological Cybernetics, 70*(2), 177–187.
16. Mari, C. F. (2000). Random networks of spiking neurons: Instability in the xenopus tadpole moto-neural pattern. *Physical Review Letters, 85*(1), 210.
17. Duch, J., & Arenas, A. (2005). Community detection in complex networks using extremal optimization. *Physical Review E, 72*(2), 027104.
18. Mistani, P., Guittet, A., Bochkov, D., Schneider, J., Margetis, D., Ratsch, C., & Gibou, F. (2018). The island dynamics model on parallel quadtree grids. *Journal of Computational Physics, 361*, 150–166.
19. Strogatz, S. H. (2001). Exploring complex networks. *Nature, 410*(6825), 268.
20. Buldyrev, S. V., Parshani, R., Paul, G., Stanley, H. E., & Havlin, S. (2010). Catastrophic cascade of failures in interdependent networks. *Nature, 464*(7291), 1025.
21. Parshani, R., Buldyrev, S. V., & Havlin, S. (2010). Interdependent networks: Reducing the coupling strength leads to a change from a first to second order percolation transition. *Physical Review Letters, 105*(4), 048701.
22. Buldyrev, S. V., Shere, N. W., & Cwilich, G. A. (2011). Interdependent networks with identical degrees of mutually dependent nodes. *Physical Review E, 83*(1), 016112.
23. Phadke, A., & Thorp, J. S. (1996). Expose hidden failures to prevent cascading outages [in power systems]. *IEEE Computer Applications in Power, 9*(3), 20–23.
24. Reis, S. D., Hu, Y., Babino, A., Andrade, J. S. Jr., Canals, S., Sigman, M., et al. (2014). Avoiding catastrophic failure in correlated networks of networks. *Nature Physics, 10*(10), 762.
25. Dobson, I., Carreras, B. A., Lynch, V. E., & Newman, D. E. (2007). Complex systems analysis of series of blackouts: Cascading failure, critical points, and self-organization. *Chaos: An Interdisciplinary Journal of Nonlinear Science, 17*(2), 026103.
26. Gao, J., Buldyrev, S. V., Stanley, H. E., & Havlin, S. (2012). Networks formed from interdependent networks. *Nature Physics, 8*(1), 40.
27. Huang, X., Gao, J., Buldyrev, S. V., Havlin, S., & Stanley, H. E. (2011). Robustness of interdependent networks under targeted attack. *Physical Review E, 83*(6), 065101.
28. Schneider, C. M., Yazdani, N., Araújo, N. A. , Havlin, S., & Herrmann, H. J. (2013). Towards designing robust coupled networks. *Scientific Reports, 3*, 1969.
29. Gao, J., Buldyrev, S. V., Havlin, S., & Stanley, H. E. (2012). Robustness of a network formed by n interdependent networks with a one-to-one correspondence of dependent nodes. *Physical Review E, 85*(6), 066134.
30. Dong, G., Gao, J., Du, R., Tian, L., Stanley, H. E., & Havlin, S. (2013). Robustness of network of networks under targeted attack. Physical Review E, 87(5), 052804.
31. Bollobás, B. (1998). Random graphs. In *Modern graph theory* (pp. 215–252). New York: Springer.
32. West, D. B., et al. (2001). *Introduction to graph theory* (Vol. 2). Upper Saddle River: Prentice Hall.
33. Bollobás, B. (2013). *Modern graph theory* (Vol. 184).Berlin/Heidelberg: Springer Science & Business Media.
34. Cohen, R., Erez, K., Ben-Avraham, D., & Havlin, S. (2001). Breakdown of the internet under intentional attack. *Physical Review Letters, 86*(16), 3682.
35. Pastor-Satorras, R., & Vespignani, A. (2001). Epidemic spreading in scale-free networks. *Physical Review Letters, 86*(14), 3200.
36. Freeman, L. C. (1978). Centrality in social networks conceptual clarification. *Social Networks, 1*(3), 215–239.
37. Friedkin, N. E. (1991). Theoretical foundations for centrality measures. *American Journal of Sociology, 96*(6), 1478–1504.
38. Sabidussi, G. (1966). The centrality index of a graph. *Psychometrika, 31*(4), 581–603.
39. Kitsak, M., Gallos, L. K., Havlin, S., Liljeros, F., Muchnik, L., Stanley, H. E., et al. (2010). Identification of influential spreaders in complex networks. *Nature Physics, 6*(11), 888.
40. Freeman, L. C. (1996). Some antecedents of social network analysis. *Connections, 19*(1), 39–42.

41. Wellman, B. (1926). The school child's choice of companions. *The Journal of Educational Research, 14*(2), 126–132.
42. Erds, P., & Rényi, A. (1960). On the evolution of random graphs. *Publication of the Mathematical Institute of the Hungarian Academy of Sciences, 5*, 17–61.
43. R. M. May, *Stability and complexity in model ecosystems*.Princeton university press, 2001, vol. 6.
44. Kauffman, S. A. (1969). Metabolic stability and epigenesis in randomly constructed genetic nets. *Journal of Theoretical Biology, 22*(3), 437–467.
45. Albert, R., Jeong, H., & Barabási, A. -L. (2000). Error and attack tolerance of complex networks. *Nature, 406*(6794), 378.
46. Jeong, H., Tombor, B., Albert, R., Oltvai, Z. N., & Barabási, A.-L. (2000). The large-scale organization of metabolic networks. *Nature, 407*(6804), 651.
47. Wagner, A., & Fell, D. A. (2001). The small world inside large metabolic networks. *Proceedings of the Royal Society of London B: Biological Sciences, 268*, 1478, pp. 1803–1810.
48. Newman, M. E. (2003). The structure and function of complex networks. *SIAM Review, 45*(2), 167–256.
49. Kempe, D., Kleinberg, J., & Tardos, É. (2003). Maximizing the spread of influence through a social network. In *Proceedings of the Ninth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 137–146).New York: ACM.
50. Marzullo, K. (1990). Tolerating failures of continuous-valued sensors. *ACM Transactions on Computer Systems (TOCS)* (Vol. 8(4), pp. 284–304).
51. Sahni, S., & Xu, X. (2005). Algorithms for wireless sensor networks. *International Journal of Distributed Sensor Networks, 1*(1), 35–56.
52. Ao, B., Wang, Y., Yu, L., Brooks, R. R., & Iyengar, S. (2016). On precision bound of distributed fault-tolerant sensor fusion algorithms. *ACM Computing Surveys (CSUR), 49*(1), 5.
53. Wu, H.-H., & Yeh, M.-Y. (2013). Influential nodes in a one-wave diffusion model for location-based social networks. In *Pacific-Asia Conference on Knowledge Discovery and Data Mining* (pp. 61–72).New York: Springer.
54. Zhang, C., Shou, L., Chen, K., Chen, G., & Bei, Y. (2012). Evaluating geo-social influence in location-based social networks. In *Proceedings of the 21st ACM International Conference on Information and Knowledge Management* (pp. 1442–1451).New York: ACM.
55. Zhu, W.-Y., Peng, W.-C., Chen, L.-J., Zheng, K., & Zhou, X. (2015). Modeling user mobility for location promotion in location-based social networks. In *Proceedings of the 21th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 1573–1582).New York: ACM.
56. Domingos, P., & Richardson, M. (2001). Mining the network value of customers. In *Proceedings of the Seventh ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 57–66).New York: ACM.
57. Brooks, R. R., & Iyengar, S. S. (1996). Robust distributed computing and sensing algorithm. *Computer, 29*(6), 53–60.
58. Bonacich, P. (1972). Factoring and weighting approaches to status scores and clique identification. *Journal of Mathematical Sociology, 2*(1), 113–120.
59. Freeman, L. C. (1977). A set of measures of centrality based on betweenness. *Sociometry, 40*, 35–41.
60. Lü, L., Zhang, Y.-C., Yeung, C. H., & Zhou, T. (2011). Leaders in social networks, the delicious case. *PLoS One, 6*(6), e21202.
61. Brin, S., & Page, L. (1998). The anatomy of a large-scale hypertextual web search engine. *Computer Networks and ISDN Systems, 30*(1–7), 107–117.
62. Radicchi, F., Fortunato, S., Markines, B., & Vespignani, A. (2009). Diffusion of scientific credits and the ranking of scientists. *Physical Review E, 80*(5), 056103.
63. Lee, S. H., Kim, P.-J., Ahn, Y.-Y., & Jeong, H. (2010). Googling social interactions: Web search engine based social network construction. *PLoS One, 5*(7), e11233.
64. Zeng, A., & Zhang, C.-J. (2013). Ranking spreaders by decomposing complex networks. *Physics Letters A, 377*(14), 1031–1035.

65. Barbieri, N., Bonchi, F., & Manco, G. (2012). Topic-aware social influence propagation models. In *2012 IEEE 12th International Conference on Data Mining (ICDM)* (pp. 81–90).New York: IEEE.
66. Zhu, W.-Y., Peng, W.-C., Chen, L.-J., Zheng, K., & Zhou, X. (2016). Exploiting viral marketing for location promotion in location-based social networks. *ACM Transactions on Knowledge Discovery from Data (TKDD), 11*(2), 25.
67. Wang, Y., Cong, G., Song, G., & Xie, K. (2010). Community-based greedy algorithm for mining top-k influential nodes in mobile social networks. In *Proceedings of the 16th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 1039–1048).New York: ACM.
68. Chen, D., Lü, L., Shang, M.-S., Zhang, Y.-C., & Zhou, T. (2012). Identifying influential nodes in complex networks. *Physica A: Statistical Mechanics and Its Applications, 391*(4), 1777–1787.
69. Zhang, X., Zhu, J., Wang, Q., & Zhao, H. (2013). Identifying influential nodes in complex networks with community structure. *Knowledge-Based Systems, 42*, 74–84.
70. Li, G., Chen, S., Feng, J., Tan, K.-L., & Li, W.-S. (2014). Efficient location-aware influence maximization. In *Proceedings of the 2014 ACM SIGMOD International Conference on Management of Data* (pp. 87–98).New York: ACM.
71. Malliaros, F. D., Rossi, M.-E. G., & Vazirgiannis, M. (2016). Locating influential nodes in complex networks. *Scientific Reports, 6*, 19307.
72. Wang, Z., Du, C., Fan, J., & Xing, Y. (2017). Ranking influential nodes in social networks based on node position and neighborhood. *Neurocomputing, 260*, 466–477.
73. Wang, Z., Zhao, Y., Xi, J., & Du, C. (2016). Fast ranking influential nodes in complex networks using a k-shell iteration factor. *Physica A: Statistical Mechanics and Its Applications, 461*, 171–181.
74. Baral, R., Wang, D., Li, T., & Chen, S.-C. (2016). Geotecs: Exploiting geographical, temporal, categorical and social aspects for personalized POI recommendation. In *2016 IEEE 17th International Conference on Information Reuse and Integration (IRI)* (pp. 94–101).New York: IEEE.
75. Liu, Y., Wei, W., Sun, A., & Miao, C. (2014). Exploiting geographical neighborhood characteristics for location recommendation. In *Proceedings of the 23rd ACM International Conference on Conference on Information and Knowledge Management* (pp. 739–748).New York: ACM.

Chapter 2
A Panorama of Interdependent Power Systems and Electrified Transportation Networks

M. Hadi Amini

Introduction

Overview

There has been an emerging concern regarding the optimal operation of power and transportation networks. In this chapter, a big picture of emerging challenges in the interdependent power systems and electrified transportation networks is introduced. The introduced networks will collaborate together to achieve sustainability in terms of operating in a more intelligent and efficient manner, providing more realistic models of interdependent networks, and modernizing the conventional frameworks. Further, an example of electric vehicle routing problem is provided to identify various effective networks in the broader context of sustainable interdependent networks.

In the second volume of Sustainable Interdependent Networks book, we focus on the interdependencies of power and transportation networks, optimization methods to deal with the computational complexity of them, and their role in future smart cities. In a related context, we further investigate other influential networks, such as communication networks. The considerable scale of such networks, due to the large number of buses in smart power grids and the increasing number of electric vehicles in transportation networks, brings a wide variety of computational complexity and optimization challenges. Although the independent optimization of these networks leads to locally optimum operation points, there is an emerging need

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to move towards obtaining the globally optimum operation point while satisfying the constraints of each network.

Motivation

Sustainable interdependent networks generally refer to a group of highly interconnected networks with specific objective and constraints, which interact with each other in a real-time fashion to achieve certain goals. As there are several time-varying components, these networks are complex and their optimal operation requires efficient computational methods [1]. They also need well-established policies to make sure that these interdependent networks are managed and operated in a cost-effective manner.

According to [2], interdependencies among networks can be classified into four major groups: Physical Interdependency, Cyber Interdependency, Geographical Interdependency, and Logical Interdependency.

There are several emerging challenges in optimal planning and operation of interdependent networks. Interdependent infrastructures can be views as interacting dynamical systems [3]. They continuously collaborate together via the communication networks and physical links to achieve sustainability. One of the examples of the emerging evolution from the stand-alone optimization of each of these networks towards a collaborative optimization approach is the transition towards smart cities by modernizing the conventional metropolitan areas and considering the effect of various networks on the others, e.g., power systems, energy networks, water networks, communication networks, and transportation networks [4]. The ultimate goal is to upgrade the current conventional cities to more intelligent, environmentally friendly, and economic cities. This will enhance the quality of life and increase the social welfare.

In this introductory chapter, I provide the potential solutions to address the challenges caused by integration of these networks. I also introduce smart city as a prominent example of sustainable interdependent networks. The main goal is to identify a roadmap towards sustainable development, not only for a smart city, but also for the whole globe.

Since the concept of Internet of Things leading to smart cities, there has been a motivation to employ sustainable ways of utilizing various technologies [5]. This paves the road towards efficient, optimal, and economic development of future cities.

Policy makers, potential stakeholder, and researchers have tried to answer questions on the emerging concerns, such as optimal operation of real-world large-scale networks. A smart city is a vision of several organizations to integrate multiple information and communication technologies [6]. It also aims at managing a city's assets including transportation systems, power grids, distributed sensor networks, water supply networks, and other community services. These complex networks act as global platforms for sustainable cities and societies. Although the independent optimization of these systems leads to sub-optimum operation points, there is a crucial need to move towards obtaining the globally optimum solution. This solution takes into account all the complexities and meets the operational limits.

A Review of the First Volume: Sustainable Interdependent Networks—From Theory to Application

The first volume of this book mainly addressed high-level concerns of the interdependent networks; provided a big picture of smart cities; introduced a scalable sustainable campus development strategy by Dr. Julie Newman, Director of Sustainability at MIT [7]; introduced security challenges of the networked control systems [8] and emerging computational techniques to deal with large-scale optimization problems; addressed the electrified transportation networks; and concluded by some of the methods to enable sustainability of power systems. Further, the social aspects of dynamic networks have been address in the first volume [9]. In [9], the importance of dynamic nature of online social networks as a remarkable factor in important problem of detecting community structure in a real-world scenario is highlighted. Based on [9] by ignoring the dynamic aspect of a social network, we would be unable to capture its evolution and consequently incapable to predict the future states of its actors. In this work, Javadi et al. [9] proposed to exploit an important characteristic of real-world social networks which is the presence of leaders. Leaders, or influential actors, are defined as high central nodes with a high potential to attract other members and hence to form a community. Considering leaders as a backbone of a community, they propose an incremental dynamic clustering method to detect new communities based on the formation and membership of leaders on the previous time step. This approach preserves temporal smoothness of the detected community structures which makes them consistent to track their evolutions over time. Note that the interdependency among networks might go beyond the explored networks in the first volume. For instance, in [10], the interdependent nature of cell aggregates is determined by the nonlinear feedback processes among neighboring cells. As this work demonstrates, these interdependencies lead to emergent phenomena that were not predictable at the individual cell level [10].

Besides social networks, the structure of physical networks by itself can influence the functionality of the network. For instance, in transportation infrastructure networks flow and wayfinding are highly correlated with the structure of the network. Modeling the structure of the network [11] and measuring spatial accessibility to different locations [12] provide effective tools for evaluating the network. Further in Volume I of this book, Morales et al. [13] presented a review of a proposed model for smart grid implementation on the Galapagos Islands. Unique characteristics of the Archipelago such as difficult-to-transport consumables and fuel from the continent, the stress on public services produced by tourism, and the sensible native flora and fauna turn the grid operation in a delicate task. An exhaustive model for considering the influence in the network of new services (distributed generation, power storage, and electric vehicles) is presented. Results of simulations of real feeders with proposed scenarios are presented; the results and the economic analysis confirm the advantages of introducing new concepts in the traditional grid transforming it on a smart grid, even so, when these benefits are easily observable and measurable (more information about the presented smart grid model for Galapagos Island can be found in [14, 15]). Security of power system operation plays a pivotal role in future power networks [16], especially in the case. In [17] authors addressed the transient stabilization of power networks using static VAR compensator (SVC) as a cost-effective and efficient solution.

There are some challenges regarding the computation burden of the emerging large-scale dynamical networks. Over the recent decades, there has been a dramatic shift with search, storage, and computing moving into datacenters by large-scale Internet service providers, and also numerous number of small- and medium-sized organizations. Today's datacenters can contain thousands of servers and typically use a multi-tier switch network to provide connectivity among the servers. Our today's world of modern datacenters still faces a number of challenges to maintain scalability, efficiency, and applications' performance. Applications running in datacenters are diverse in terms of CPU, memory, data, and communication bandwidth consumption. The principal bottleneck is often the communication requirement for exchanging the intermediate data pieces among the servers, as a result of running these applications in datacenters. Such communications can account for a large portion of the job completion time, and hence can have a significant impact on application latency. Therefore, to maintain efficiency and quality of service, we need efficient algorithms to make better use of both network and server resources in datacenters. There has been significant research on designing low-complexity, congestion-aware flow scheduling algorithms that make better use of network resources (for more details see [18]). Shafiee and Ghaderi [18] proposed a low-complexity, congestion-aware algorithm that routes the flows in an online fashion and without splitting them among available paths in the network.

In the first volume of this book, Khorasani [19] addressed high performance and scalable graph computation. In this chapter, he discussed challenges of processing large and real-world graphs such as social networks using GPUs. Efficiently exploiting GPU parallel computing power necessitates revisiting existing data structures and solutions. To this end, he introduced GPU-friendly graph representations that better fit GPU off-chip memory access requirements. These representations and the performance they provide are extensively evaluated in [20]. Khorasani et al. also presented a dynamic task decomposition scheme inspired by CTE technique [21] for GPU threads to effectively parallelize computing the irregular-sized neighbor list of vertices. KiTES [22] analyzes the supremacy of this technique. In addition, they offered an approach that allows scaling of computation over multiple GPUs. More information on vertex refinement technique is presented in [23] elaborately. These solutions are agnostic with respect to the underlying graph features such as levels of sparsity, and therefore well suited for processing real-world graphs with power law degree distribution. In the context of power and transportation networks, there are several studies focused on distributed algorithms to deal with the complex nature of the optimization problems in these two networks. Lagrangian-based decentralized solutions to solve economic dispatch in power systems are discussed and compared in [24]. Mohammadi et al. [25] presented a novel approach to deal with the collaborative optimal power flow considering both distribution and transmission system operators. Further, Mohammadi et al. proposed a class of distributed algorithms to deal with the large-scale optimization problems in transportation networks (to solve the cooperative charging scheduling of electric vehicles [26]). An overview of decoposition methods to deal with the large-scale optimal pwoer flow problem is provided by [27]. A comprehensive review of distributed algorithms for power networks is provided in [28]. A multi-agent-based framework is presented in [29] to reduce the computation burden of centralized optimization problem for power distribution network load management. Further, Amini et al. [30] presented a hierarchical solution to deal with the large-scale optimization problem of electric vehicle charging station. Their method leverages the decomposable structure of the optimization problem to implement Dantzig-Wolfe decomposition and solve the small-scale problems of each electric vehicle locally while exchanging limited information with the central unit at the charging station.

Another aspect of interdependent power and transportation networks is privacy and security of power systems [31, 32] as well as information privacy in transportation networks [33].

Detection and localization of fault events in power grids are carried out by collecting voltage and current measurements from the network. While local measurements potentially provide relevant information about the fault events, collecting more measurements may lead to more reliable decisions. However, due to the large-scale and geographical expansion of power grids, data collection is expensive and time consuming. On the other hand, fast detection of fault events plays a pivotal role in enhancing the overall reliability of power grid. In order to strike a balance between the quality of the decisions and the costs of data collection, a subsection of the grid that is more informative about the underlying fault event should be observed. Authors in [32] provide a stochastic framework for specifying the optimal data collection. This line of work capitalizes on the strong correlation structures observed in the measurements from different buses of the network. A sequential and data-adaptive approach is devised, which collects data over time and progressively identifies the most likely locality that may be faulty, from which it collects more data. It is shown that the correlation structure of the measurements is governed by the topology of the grid as well as the transmission-line reactance values. The proposed selection rule for data collection assigns a metric to each bus, which is a function of the observed data and the parameters of the correlation structure. Further, an error detection method is proposed in [34] which leverages the sparsity of admittance matrix.

In the first volume of the book, Najafi et al. [35] proposed a decentralized control of DR using a multi-agent method based on a Q-learning algorithm. This algorithm can guarantee end-user privacy and make them independent of aggregation entities.

Each agent is participating in the electrical market with implementing a market strategy. In this strategy, DR-enabled customers will participate in the market based on their energy requirements. In other words, every single consumer adapts its bidding and buying strategy over time according to the market outcomes, considering energy supply such as small-scale renewable energy generators. The results of the decentralized method are compared with a centralized aggregator-based approach that shows the effectiveness of the proposed decentralized DR market. Decentralized control strategies are measures of future smart systems in terms of economic and technical aspects that provide high speed and low computation cost, and preserve the privacy. From the economic perspective, a market-based control scheme is presented in [36] to minimize the billing costs of responsive demands with the minimum impact on their privacy and satisfaction. The responsive demands are modeled as agents who bid to the day-ahead and real-time electricity markets through their energy management systems. In order to maintain the satisfaction and privacy of consumers in the demand response programs, a decentralized DR-based algorithm is developed considering the competition-based participation of consumers by a performance-based reward and recognition strategy. From the electricity market perspective, a multilayer agent-based model is proposed in [37] for modeling the behavior of market participants. Further, in [38], a decentralized approach is presented to model the uncertainty of renewable generation unit using conditional value at risk.

In the first volume of the book, Rahman et al. [39] provided a brief summary of bio-inspired computational intelligence (CI) techniques for plug-in electric vehicle charging optimization. From the many concerns regarding PEV charging optimization, this chapter is devoted to the following major issues: the application and performance of bio-inspired CI techniques as well as the necessity of PEV charging optimization in smart grid environment. Additionally, the chapter also addresses the applications of bio-inspired CI for PEV charging optimization. It also classifies the optimization problems in terms of various charging alternatives. Further, in [40], gravitational search algorithm (GSA) and particle swarm optimization (PSO) technique were applied for intelligent allocation of energy to the plug-in hybrid electric vehicles (PHEVs) considering constraints such as energy price, remaining battery capacity, and remaining charging time; they optimized the state of charge (SoC). Simulation results found for maximizing the highly nonlinear fitness function assess the performance of both the methods in terms of computation time and global best fitness values. The simulation results in [41] evaluated the performance of standard PSO, accelerated version of PSO (APSO), GSA, and the hybrid PSO-GSA. This research study suggests that PSO-GSA technique has a great future for SoC optimization although it is computational exhaustive. Another chapter in the first volume describes the invention of vehicle-to-grid technology (V2G), whereby electric vehicles such as BEV and PHEV are connected to a system which can interchangeably charge the vehicles or send electricity from the vehicles to the power grid [42]. This bidirectional communication setup allows PHEV to obtain electricity through the power grid while the extra electricity from the vehicles can be liquidated into the grid [42]. This technology is developed in response to the challenges for conventional vehicles which rely on fossil fuel to be operated. High and volatile oil price is taking its toll on the consumers who have to fork out more money to use their vehicles. Furthermore, the technology can add capacity to the power-driven grid during peak times [43]. More importantly, the dependence on oil to run vehicles has its adverse disadvantages of polluting the environment and contributing to the climate change [44, 45]. This chapter then introduces its objective that is to classify the problems of V2G adoption and their root causes, by observing the consumer adoption perception regarding the V2G technology. Theory of planned behavior has been used as the framework for the study. The results have shown the important factors hindering consumers from adopting the technology such as lack of information such as on potential hazards of the new products, vehicle efficiency, price, and size [42]. To solve this, the author recommends utilizing social media or mass media and social networks to penetrate the market with information on the technology. Consumers who are concerned with the potential cost of adopting can be addressed with economic assistance. Lastly, awareness on ecological and environmental conservation might sway the consumers to adopt the technology too.

In another study, [45] produced a review study on the adoption behavior of consumers towards PHEV/EV in Malaysia. As mentioned above, the V2G technology depends on initial adoption of PHEV/EV which allows the vehicles to connect to the electrical grid for the transfer of electricity to and from the vehicles [42]. This study used the framework of theory of planned behavior (TPB) to explain the adoption trend of PHEV/EV among Malaysian consumers. To add to the depth of the discussion, environmental concern is incorporated into the theory to explain its influence in the adoption decision of the consumers towards PHEV/EV [46]. This is because the technology is expected to improve the environment and reduce the dependency on fossil fuel. Thus, this study looks into the literature, searching for publication documents related to the adoption of PHEV/EV. The results have revealed several key notes for the adoption decision among consumers. It has been found that the level of awareness on environmental concern is important according to the literature. Other factors, including age, gender, education level, willingness to pay, and income, also have been found to be influential, although they are not directly related to environmental awareness [45]. The implication of the paper highlights the need to promote the technology as environmentally friendly as well as cost effective.

Another paper by [43] delves into the adoption of PHEV/EV technology, specifically looking at the effectiveness of the PHEV/EV charging infrastructures. The charging component is a major issue as it combines two technologies together, that is, PHEV/EV technology and V2G technology [42]. The charging system is thus critical to the operation of electric vehicles. Conventional power grid might not be able to handle the charging of the PHEV/EV in the future when it is expected to supply enough energy to a mass number of electric vehicles as predicted by researchers. In order to solve the load burden of the electric grid, researchers utilize optimization techniques. This paper hence reviews literature documents in which researchers used optimization methods to solve the charging infrastructure issue. From the review, the author has found that the optimization methods used are numerous, indicating the lack of central approach to the issue [53]. The results from the optimization revealed a need for a smart integrated charging system which can optimize its usage while maximizing revenue to aggregators as well as giving easiness and peak load shaving to the utility provider at low charges for the vehicle charging. The author also points out the need to integrate electricity generated from diverse renewable resources into the charging system [47].

Decentralized energy systems provide promising opportunities for deploying renewable energy resources which are locally available, particularly in the urban areas. They can be used as an alternative solution to the existing centralized energy system (e.g., fossil fuel power plants). For example, solar photovoltaic (PV) deployment on the existing building rooftops has been proven to be one of the most viable sustainable solutions. Decentralized energy systems require, however, the design of smart grids along with the estimation of both energy supply and demand values in the location of interest in order to be efficiently implemented. A thorough review of different methods so that to estimate large-scale solar rooftop PV potential for smart grid integration was conducted by Assouline et al. [48]. The study, included in the first volume of the book, discusses both the main concepts and the application of different methods to estimate large-scale solar rooftop PV potential. More specifically, the chapter discusses various methods to estimate (1) the physical potential, which represents the total energy received from the sun by urban areas; (2) the geographic or urban potential, which reflects the constraints on the locations where the solar energy can be captured and used for PV installations; and (3) the technical potential, which translates into the final electrical energy output obtained from the system, using the technical characteristics of the PV technology. In these steps, the difficulty resides in the estimation of a few critical variables, which are mainly (1) the horizontal global, diffuse, direct, and extraterrestrial solar radiation; (2) the shadowing effects over rooftops; (3) the rooftops slope and aspect distributions; and (4) the available roof surface area for PV installation. The discussed methods include the following: the use of predefined coefficients, geographic information system (GIS) processing, sampling methods using building types, remote sensing data processing, particularly LiDAR (light detection and ranging) data and satellite images, and more recently machine learning methods (e.g., support vector machine and random forests) [49–51]. After the concepts behind the methods are explained, they are compared with their main advantages and disadvantages highlighted. A small guide is also provided for when to use them, depending on the available data and the situation at hand.

Assouline et al. [49] recently presented a new methodology combining machine learning, GIS, and physical models to estimate the solar technical rooftop PV potential, and applied it to Switzerland in order to estimate its PV potential for each of its municipalities [49]. The methodology aims at using remote sensing and GIS data so as to build machine learning that allows the estimation of multiple variables of interest (horizontal solar radiation, shadowing effects, slope, direction, shape of rooftops, and available rooftop area for PV installation) over the whole territory. These variables of interest are then combined using classical solar physical models. An improved strategy was also suggested [50] to estimate the potential at 200m x 200m pixel level. This new strategy includes a roof shape, slope, and direction classification at the national level [51].

Intelligent transportation networks include several aspects. Khazraeian et al. [52] proposed two incident detection methods using connected vehicle data. The first method referred to as "average acceleration distribution method" uses the distribution of vehicle acceleration in each segment under no incident condition and detects the abnormality in the acceleration behavior by comparing the measured test segment average acceleration with a percentile threshold of the used distributions. The second proposed method uses the likelihood ratio method to detect the incidents. The method, referred to as likelihood ration test (LRT) method, measures the likelihood of the measurements belonging to the incident case and no incident case. If the likelihood ratio is more than a threshold, the incident occurrence is declared in the corresponding. The results showed that the second method outperforms the first one. Following the incident detection research, Khazraeian et al. [53] extended the research to the back of queue estimation. The back of queue resulted from the incident was estimated using connected vehicle data and compared to the ones estimated by the point detector data. Vehicle speed measurements were used for back of queue estimation. The study also investigated the safety benefits of queue warning system (QWS) in the presence of connected vehicles in the traffic stream. The results indicated that a relatively low market penetration, around 3–6%, for the congested freeway examined in this study, is sufficient for accurate and reliable estimation of the queue length. The safety evaluation of the QWS showed that the number of rear-end collisions was reduced by 15% due to the activation of queue warning system and dissemination on the back of location to the drivers upstream of the incident. Another aspect of modern transportation networks is the large-scale interaction of electric vehicles and its effects on power networks. In [54], a comprehensive framework and its required methodologies are proposed to solve an iterative least cost routing problem for electrified vehicles. This framework assumed the availability of communication infrastructure between the electrified vehicles and charging stations. It also takes varying electricity price signals, charging demand, arrival time, traffic conditions, and power network constraints into account. In [55], a framework for modeling electric vehicle parking lots in expansion planning of power distribution networks is proposed. This approach models the uncertainty of vehicle-to-grid (V2G) technology using Z-number. In [56] a two-stage framework is proposed to find the optimal location and size of electric vehicle parking lots and distributed renewable resources simultaneously. The proposed approach not only takes the economic objectives of parking lot investor but also considers the technical constraints of power distribution network, such as loss minimization [56].

There have been several efforts in the literature to solve computationally expensive and large-scale optimization problems. Chaovalitwongse et al. in [57] proposed an approach to reduce the multi-quadratic 0–1 programming problem to a linear mixed 0–1 one. Further, Prokopyev et al. [58] investigated the complexity of 0–1 programming problems. They have shown that determining a global maximizer to these problems with unique solution is NP-hard. According to Veremyev et al. [59], critical element detection of graphs has been investigated through an integer programming approach. Their proposed approach aims at minimizing the connectivity and cohesiveness of the analyzed graph [59]. Bilevel optimization is a field in the mathematical programming that attracted several real-world and theoretical attentions [60]. Bard in [61] and Colson et al. [60] provided comprehensive reviews of the applications for bilevel optimization. In [62] the application of modified simplex method to solve bilevel optimization is investigated. Beheshti et al. in [63, 64] proposed an algorithm to obtain the exact solution to a class of nonlinear bilevel problems. Moreover, branch-and-bound method has been deployed to solve linear bilevel programming [65]. Deb et al. [66] proposed an evolutionary algorithm to solve bilevel multi-objective optimization problems.

An Example of Interdependent Power and Transportation Networks

Here, I introduce the conceptual framework of interdependent power systems and electrified transportation networks. More specifically, I start with these two existing interdependent networks, as subsets of smart cities, which are modelled independently in the current frameworks and practical solutions. It means their interdependencies are ignored in the current setting. I will then explain how the interaction of these two networks and the corresponding interdependencies can improve the operational performance of each network, enhance the feasibility of the obtained solutions (compared with the real-world scenarios rather than current models with different orders of simplification), increase the social welfare, and minimize the cost for the end users. Note that having a comprehensive vision about the interdependencies among multiple networks does not only contributes to optimal operation of all subsets, but also enhances the secure operation of each network. For instance, power system resiliency could be ensured by properly capturing the interdependent interaction of power systems with other networks [67].

Power systems are mainly designed to provide reliable electricity to the customers using the available resources, including generation units, transmission networks, and distribution systems. There has been an emerging concept, referred to as smart grid, which aims at upgrading the conventional power systems by taking advantage of advanced metering infrastructure, communication networks, and intelligent computation techniques. There is also a promising transition from fossil fuel-based transportation networks towards electrified transportation networks. This relies on electric cars to improve the energy efficiency, reduce the air pollution, and also reduce the total travel cost for each trip. All in all, these transitions (from conventional power grids to smart grids, and from conventional transportation networks towards intelligent electrified transportation networks) are under the umbrella of network of networks, i.e., there is an emerging transition from the independently operating networks in the conventional cities to interdependently operating network of networks in the smart cities framework.

Currently, various large-scale networks are optimizing their operation point only considering their own limits, decision parameters, and objectives. They just consider the influential factors which are directly affecting their solution. For instance, power system operators solve their optimization problem to achieve certain objectives, such as minimizing the cost of generating electricity, minimizing the greenhouse gas emissions, increasing the portion of renewable resources, or increasing the reliability of the power supply. Another example is the transportation network. Currently, there are several applications to find the optimal route to travel between two points on the geographical map. These solutions have some limited preferences, such as traffic condition modeling, choosing the fastest route, or minimizing the number of traffic lights. However, there is a highly missing dimension in all these operational optimizations.

In order to analyze the critical infrastructure and interdependent networks, the first step is to determine the common variables, and mutually influential factors among these networks. For instance, I take an in-depth look into the two mentioned networks, power and transportation. Electric cars are the common point that connects these two networks. Their routing optimization is affected by transportation networks. Further, their battery charging preference is affected by power systems. On the other hand, their routing decision affects the transportation networks. Further, their charging decision affects the electric load demand in the power systems. Consequently, the main connecting point of power systems and electrified transportation networks is electric vehicle. So far, we only could identify two layers of interdependency in the electric car's route optimization/charging scheduling problem. Each car needs to share some information with the charging station agent, each charging station operator needs to talk with power system agent, and transportation network operators should update the traffic database according to the optimal decision of each driver. Hence, we need an efficient communication platform to enable the required information exchange among electric vehicles, charging stations, power systems, and transportation networks, more specifically, among drivers, power system operators, transportation network operators, and charging network operators. Moreover, due to the real-time nature of the information sharing, we need to make sure that the privacy of various agents is not compromised due to the information sharing, such as the location privacy of the vehicles. This will add another layer to the layers that I explained so far. We have power systems, transportation networks, charging stations network, communication infrastructure, and information security layer.

There is still an influential network, which is missing from our puzzle to fully model and illustrate the routing decision from the starting point to the destination. This influential layer is societal network, i.e., the interaction of the human behavior with the mentioned layers. Societal network is the key to smart cities and interdependent networks! This is, in my view, by far the most complicated network that should be taken into consideration. Decision-making of each social actor (such as individuals and organization) and the social interactions among these actors are highly stochastic. This happens because of the various decision-making parameters. Figure 2.1 represents an overview of these interdependencies among

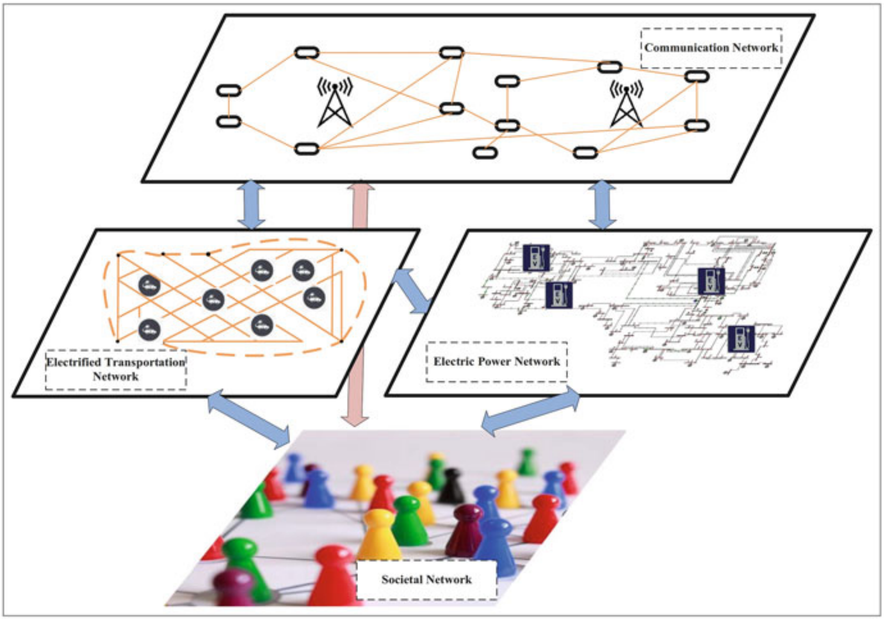

Fig. 2.1 Overview of interdependencies among power, electrified transportation, societal, and communication networks

power, electrified transportation, societal, and communication networks. Although all these networks are involved in the decision-making of an EV driver, there have been few studies with the main goal of considering all these networks and their corresponding interdependencies (see [54] for example). On the other hand, there is an extensive literature on the effects of electrified vehicles on smart grids while ignoring the there networks, such as societal network or communication networks [68–75]. In [76], authors addressed the missing dimension of vehicle to grid technology by investigating the consumer acceptance[1]. Further, the large-scale nature of social networks makes them more complicated.

How does the society react to a specific charging strategy with a specific pricing scheme? How flexible are the users facing these emerging technologies? These are examples of open questions in the context of interdependent power systems and electrified transportation networks.

Further research is required to identify the impact of social network dynamics on the interdependent networks.

[1]More recent studies in [77–97] tackled different aspects of integrating electric vehicles into power systems.

An Overview of the Second Volume

The second volume of sustainable interdependent networks is organized to first introduce complex networks and their corresponding challenges.

This volume is organized in three major parts:

Part I: Complex Networks: Theory and Real-World Applications

This part includes Chaps. 3, 4, and 5. Chapter 3 introduces smart cities as emerging real-world examples of interdependent networks. Chapter 4 introduces the powerful machinery of renormalization group theory developed to investigate phase transitions in many-body systems of condensed matter physics and justifies the applicability of renormalization group to the study of interdependent networks. Chapter 5 complements Chap. 4 by providing proof of concept for the renormalization concept.

Part II: Intelligent Electrified Transportation Networks

This part addresses various aspects of modern transportation networks, from the autonomous cars to intelligent transportation systems development. It includes Chaps. 6, 7, 8, and 9. Chapter 6 investigates two emerging applications for connected vehicles in the context of intelligent transportation systems (ITS), i.e., queue warning and automatic incident detection. Chapter 7 studied the promising technology of autonomous vehicles by highlighting the ethical implications of the autonomous technology to be further researched and scrutinized in order to establish trust between human and machine. Chapter 8 proposed an approach for trajectory analysis which is an essential function in intelligent transportation systems and by applying it for the spatial trajectory data, a wide range of transportation problems can be solved. Finally, Chap. 9 concludes this part by investigating the application of vehicle-to-grid technology for primary frequency control in power systems. This chapter is a notable example of interdependent interaction of power systems and electrified transportation networks.

Part III: Sustainable Power Networks

The last part of this volume addressed emerging topics in modern power systems. Chapter 10 provides a thorough review on demand response programs. Chapter 11 analyzes the impact of electricity consumers' behavior on power system reliability.

Chapter 12 proposed to deploy system of systems concept for complex power system optimization problems. Chapter 13 proposed a sustainable supply chain management which is applicable to various range of practical problems in the context of sustainability. Finally, Chapter 14 studies protection schemes in sustainable microgrids.

References

1. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P., Blaabjerg, F., & Madni, A. (2018). *Sustainable interdependent networks: From theory to application*. Cham: Springer.
2. Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems, 21*(6), 11–25.
3. Rosato, V., Issacharoff, L., Tiriticco, F., Meloni, S., Porcellinis, S., & Setola, R. (2008). Modelling interdependent infrastructures using interacting dynamical models. *International Journal of Critical Infrastructures, 4*(1-2), 63–79.
4. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P., Blaabjerg, F., & Madni, A. (Eds.). (2018). A panorama of future interdependent networks: From intelligent infrastructures to smart cities. In *Sustainable interdependent networks* (pp. 1–10). Springer, Cham.
5. Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of things for smart cities. *IEEE Internet of Things Journal, 1*(1), 22–32.
6. Hafedh, C., Nam, T., Walker, S., Ramon Gil-Garcia, J., Mellouli, S., Nahon, K., et al. (2012). Understanding smart cities: An integrative framework. In *45th Hawaii International Conference on System Sciences (HICSS)* (pp. 2289–2297). Maui: IEEE.
7. Newman, J. (2018). Calling for a next-generation sustainability framework at MIT. In M. H. Amini, K. G. Boroojeni, S. S. Iyengar, P. M. Pardalos, F. Blaabjerg, & A. M. Madni (Eds.), *Sustainable interdependent networks* (pp. 13–20). Cham: Springer.
8. Sargolzaei, A., Sargolzaei, A., Abbaspour, A., Al Faruque, M. A., Eddin, A. S., & Yen, K. (2018). Security challenges of networked control systems. In *Sustainable interdependent networks* (pp. 77–95). Cham: Springer.
9. Seyed, J. S. H., Gharani, P., & Khadivi, S. (2018). Detecting community structure in dynamic social networks using the concept of leadership. In *Sustainable interdependent networks* (pp. 97–118). Cham: Springer.
10. Mistani, P., Guittet, A., Poignard, C., & Gibou, F. (2018). A parallel Voronoi-based approach for mesoscale simulations of cell aggregate electropermeabilization. *arXiv, 1802*, 01781.
11. Gharani, P., & Delavar, M. R. (2008). Formalization of a knowledge-based approach for representing and learning spatial structure of a large-scale space. *World Applied Sciences Journal, 3*(1), 119–126.
12. Gharani, P., Stewart, K., & Ryan, G. L. (2015). An enhanced approach for modeling spatial accessibility for in vitro fertilization services in the rural Midwestern United States. *Applied Geography, 64*, 12–23.
13. Morales, D. X., Besanger, Y., & Medina, R. D. (2018). Complex distribution networks: Case study Galapagos Islands. In *Sustainable interdependent networks* (pp. 251–281). Cham: Springer.
14. Morales, D. X., Besanger, Y., Sami, S., & Bel, C. A. (2017). Assessment of the impact of intelligent DSM methods in the Galapagos Islands toward a Smart Grid. *Electric Power Systems Research, 146*, 308–320.
15. Morales, D. X., Besanger, Y., Alvarez Bel, C., & Medina, R. D. (2016). Impact assessment of new services in the Galapagos low voltage network. In *2016 IEEE PES Transmission & Distribution Conference and Exposition-Latin America (PES T&D-LA)*. Morelia: IEEE.

16. Boroojeni, K. G., Amini, M. H., & Iyengar, S. S. (2017). *Smart grids: Security and privacy issues*. New York: Springer.
17. Amini, M. H., Jaddivada, R., Hoseinzadeh, B., Mishra, S., & Mozafar, M. R. (2018). Optimal SVC allocation in power systems for loss minimization and voltage deviation reduction. In *Sustainable interdependent networks* (pp. 221–232). Cham: Springer.
18. Shafiee, M., & Ghaderi, J. (2017). A simple congestion-aware algorithm for load balancing in datacenter networks. *IEEE/ACM Transactions on Networking, 25*(6), 3670–3682.
19. Khorasani, F. (2018). High performance and scalable graph computation on GPUs. In M. Amini, K. Boroojeni, S. Iyengar, P. Pardalos, F. Blaabjerg, & A. Madni (Eds.), *Sustainable interdependent networks* (pp. 67–75). Cham: Springer.
20. Khorasani, F., Vora, K., Gupta, R., & Bhuyan, L. N. (2014). CuSha: Vertex-centric graph processing on GPUs. In *Proceedings of the 23rd International Symposium on High-Performance Parallel and Distributed Computing* (pp. 239–252). Vancouver: ACM.
21. Khorasani, F., Rowe, B., Gupta, R., & Bhuyan, L. N. (2016). Eliminating intra-warp load imbalance in irregular nested patterns via collaborative task engagement. In *Parallel and Distributed Processing Symposium, 2016 IEEE International* (pp. 524–533). Chicago: IEEE.
22. Khorasani, F., Vora, K., Gupta, R., & Bhuyan, L. N. (2017). Enabling work-efficiency for high performance vertex-centric graph analytics on GPUs. In *Proceedings of the Seventh Workshop on Irregular Applications: Architectures and Algorithms* (p. 11). Denver: ACM.
23. Khorasani, F., Gupta, R., & Bhuyan, L. N. (2015). Scalable SIMD-efficient graph processing on GPUs. In *2015 International Conference on Parallel Architecture and Compilation (PACT)* (pp. 39–50). San Francisco: IEEE.
24. Amini, M. H., Jaddivada, R., Mishra, S., & Karabasoglu, O. (2015). Distributed security constrained economic dispatch. In *IEEE Innovative Smart Grid Technologies—Asia (ISGT ASIA)* (pp. 1–6). Bangkok: IEEE.
25. Mohammadi, A., Mehrtash, M., & Kargarian, A. (2018). Diagonal quadratic approximation for decentralized collaborative TSO+DSO optimal power flow. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2018.2796034.
26. Mohammadi, J., Hug, G., & Kar, S. (2016). A fully distributed cooperative charging approach for plug-in electric vehicles. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2016.2633416.
27. Amini, M. H., Bahrami, S., Kamyab, F., Mishra, S., Jaddivada, R., et al. (2018). Decomposition methods for distributed optimal power flow: Panorama and case studies of the DC model. In *Classical and Recent Aspects of Power System Optimization* (pp. 137–155).
28. Molzahn, D. K., Dörfler, F., Sandberg, H., Low, S. H., Chakrabarti, S., Baldick, R., & Lavaei, J. (2017). A survey of distributed optimization and control algorithms for electric power systems. *IEEE Transactions on Smart Grid, 8*(6), 2941–2962.
29. Amini, M. H., Nabi, B., & Haghifam, M.-R. (2013). Load management using multi-agent systems in smart distribution network. In *Power and Energy Society General Meeting (PES)*. Vancouver: IEEE.
30. Amini, M. H., McNamara, P., Weng, P., Karabasoglu, O., & Xu, Y. (2017). Hierarchical electric vehicle charging aggregator strategy using Dantzig-Wolfe decomposition. *IEEE Design and Test Magazine*. https://doi.org/10.1109/MDAT.2017.2759505.
31. Boroojeni, K. G., Amini, M. H., & Iyengar, S. S. (2017). End-user data privacy. In *Smart grids: Security and privacy issues* (pp. 85–92). Berlin: Springer International Publishing.
32. Heydari, J., & Tajer, A. Quickest localization of anomalies in power grids: A stochastic graphical framework. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2017.2666543.
33. Boroojeni, K. G., Amini, M. H., & Iyengar, S. S. (2017). Mobile user data privacy. In *Smart grids: Security and privacy issues* (pp. 93–110). Berlin: Springer International Publishing.
34. Amini, M. H., Rahmani, M., Boroojeni, K. G., Atia, G., Iyengar, S. S., & Karabasoglu, O. (2016). Sparsity-based error detection in DC power flow state estimation. In *IEEE International Electro/Information Technology Conference (EIT 2016)*. Grand Forks: IEEE.

35. Najafi, S., Talari, S., Gazafroudi, A. S., Shafie-khah, M., Corchado, J. M., & Catalão, J. P. S. (2018). Decentralized control of DR using a multi-agent method. In *Sustainable interdependent networks* (pp. 233–249). Cham: Springer.
36. Shafie-khah, M., Osório, G. J., Catalão, J. P. S. (2017, August 27–September 1). A decentralized privacy-based electricity market scheme for responsive demands. In *Proceedings of the 10th Bulk Power Systems Dynamics and Control Symposium—IREP'2017, Espinho, Portugal*.
37. Shafie-khah, M., & Catalão, J. P. S. (2015). A stochastic multi-layer agent-based model to study electricity market participants behavior. *IEEE Transactions on Power Systems, 30*(2), 867–881.
38. Bahrami, S., & Amini, M. H. (2018). A decentralized trading algorithm for an electricity market with generation uncertainty. *Applied Energy, 218*, 520–532.
39. Rahman, I., & Mohamad-Saleh, J. (2018). Plug-in electric vehicle charging optimization using bio-inspired computational intelligence methods. In *Sustainable interdependent networks* (pp. 135–147). Cham: Springer.
40. Rahman, I., Vasant, P., Singh, B. S. M., & Abdullah-Al-Wadud, M. (2015). Swarm intelligence-based optimization for PHEV charging stations. In *Handbook of research on swarm intelligence in engineering* (pp. 374–405). Hershey: IGI Global.
41. Vasant, P. M., Rahman, I., Singh, B. S. M., & Abdullah-Al-Wadud, M. (2016). Optimal power allocation scheme for plug-in hybrid electric vehicles using swarm intelligence techniques. *Cogent Engineering, 3*(1). https://doi.org/10.1080/23311916.2016.1203083.
42. Adnan, N., Nordin, S. M., & Althawadi, O. M. (2018). Barriers towards widespread adoption of V2G technology in smart grid environment: From laboratories to commercialization. In *Sustainable interdependent networks* (pp. 121–134). Berlin: Springer.
43. Rahman, I., Vasant, P. M., Singh, B. S. M., Abdullah-Al-Wadud, M., & Adnan, N. (2016). Review of recent trends in optimization techniques for plug-in hybrid, and electric vehicle charging infrastructures. *Renewable and Sustainable Energy Reviews, 58*, 1039–1047.
44. Adnan, N., Nordin, S. M., Rahman, I., & Rasli, A. M. (2017). A new era of sustainable transport: An experimental examination on forecasting adoption behavior of EVs among Malaysian consumer. *Transpiration Research Part A Policy Practice, 103*, 279–295.
45. Adnan, N., Nordin, S. M., & Rahman, I. (2017). Adoption of PHEV/EV in Malaysia: A critical review on predicting consumer behaviour. *Renewable and Sustainable Energy Reviews, 72*, 849–862.
46. Adnan, N., Nordin, S. M., Rahman, I., Vasant, P., & Noor, M. A. (2017). An overview of electric vehicle technology: A vision towards sustainable. In T. Essaki (Ed.), *Green marketing and environmental responsibility in modern corporations* (p. 198). Hershey: IGI Global.
47. Adnan, N., Nordin, S. M., Rahman, I., Vasant, P. M., & Noor, A. (2017). A comprehensive review on theoretical framework-based electric vehicle consumer adoption research. *International Journal of Energy Research, 41*(3), 317–335.
48. Assouline, D., Mohajeri, N., & Scartezzini, J. L. (2018). Estimation of large-scale solar rooftop PV potential for smart grid integration: A methodological review. In *Sustainable interdependent networks* (pp. 173–219). Cham: Springer.
49. Assouline, D., Mohajeri, N., & Scartezzini, J. L. (2017). Quantifying rooftop photovoltaic solar energy potential: A machine learning approach. *Solar Energy, 141*, 278–296.
50. Assouline, D., Mohajeri, N., & Scartezzini, J. L. (2018). Large-scale rooftop solar photovoltaic technical potential estimation using random forests. *Applied Energy, 217*, 189–211.
51. Assouline, D., Mohajeri, N., & Scartezzini, J. L. (2017, October). Building rooftop classification using random forests for large-scale PV deployment. In *Earth resources and environmental remote Sensing/GIS Applications VIII* (Vol. 10428, p. 1042806). International Society for Optics and Photonics.
52. Khazraeian, S., Hadi, M., & Xiao, Y. (2016, January). Detection of freeway incidents based on vehicle acceleration measurements using connected vehicle data. In *Proceedings of the 95th Annual Meeting of the Transportation Research Board, Washington, D.C.*

53. Khazraeian, S., Hadi, M., & Xiao, Y. (2017). Safety impacts of queue warning in a connected vehicle environment. *Transportation Research Record: Journal of the Transportation Research Board, 2621*, 31–37.
54. Amini, M. H., & Karabasoglu, O. (2018). Optimal operation of interdependent power systems and electrified transportation networks. *Energies Journal, 11*, 196.
55. Nasri, A. H., Abdollahi, A., Rashidinejad, M., & Amini, H. M. (2018). Probabilistic-possibilistic model for a parking lot in the smart distribution network expansion planning. *IET Generation, Transmission & Distribution, 12*(13), 3363–3374.
56. Amini, M. H., Moghaddam, M. P., & Karabasoglu, O. (2017). Simultaneous allocation of electric vehicles' parking lots and distributed renewable resources in smart power distribution networks. *Sustainable Cities and Society, 28*, 332–342.
57. Chaovalitwongse, W., Pardalos, P. M., & Prokopyev, O. A. (2004). A new linearization technique for multi-quadratic 0–1 programming problems. *Operations Research Letters, 32*(6), 517–522.
58. Prokopyev, O. A., Huang, H.-X., & Pardalos, P. M. (2005). On complexity of unconstrained hyperbolic 0–1 programming problems. *Operations Research Letters, 33*(3), 312–318.
59. Veremyev, A., Prokopyev, O. A., & Pasiliao, E. L. (2014). An integer programming framework for critical elements detection in graphs. *Journal of Combinatorial Optimization, 28*(1), 233–273.
60. Colson, B., Marcotte, P., & Savard, G. (2007). An overview of bilevel optimization. *Annals of Operations Research, 153*(1), 235–256.
61. Bard, J. F. (2013). *Practical bilevel optimization: Algorithms and applications* (Vol. 30). Berlin: Springer Science & Business Media.
62. Campêlo, M., & Scheimberg, S. (2000). A note on a modified simplex approach for solving bilevel linear programming problems. *European Journal of Operational Research, 126*(2), 454–458.
63. Beheshti, B., Özaltın, O. Y., Hosein Zare, M., & Prokopyev, O. A. (2015). Exact solution approach for a class of nonlinear Bilevel knapsack problems. *Journal of Global Optimization, 61*(2), 291–310.
64. Beheshti, B., Prokopyev, O. A., & Pasiliao, E. L. (2016). Exact solution approaches for bilevel assignment problems. *Computational Optimization and Applications, 64*(1), 215–242.
65. Hansen, P., Jaumard, B., & Savard, G. (1992). New branch-and-bound rules for linear bilevel programming. *SIAM Journal on Scientific and Statistical Computing, 13*(5), 1194–1217.
66. Deb, K., & Sinha, A. (2009). Solving bilevel multi-objective optimization problems using evolutionary algorithms. In *International conference on evolutionary multi-criterion optimization*. Berlin: Springer.
67. Gholami, A., Shekari, T., Amirioun, M. H., Aminifar, F., Amini, M. H., & Sargozalei, A. (2018). Toward a consensus on the definition and taxonomy of power system resilience. *IEEE Access, 6*, 32035–32053.
68. Amini, M. H., Kargarian, A., & Karabasoglu, O. (2016). ARIMA-based decoupled time series forecasting of electric vehicle charging demand for stochastic power system operation. *Electric Power Systems Research, 140*, 378–390.
69. Mozafar, M. R., Amini, M. H., & Moradi, M. H. (2018). Innovative appraisement of smart grid operation considering large-scale integration of electric vehicles enabling V2G and G2V systems. *Electric Power Systems Research, 154*, 245–256.
70. Alizadeh, M., Wai, H., Goldsmith, A., & Scaglione, A. (2018). Retail and wholesale electricity pricing considering electric vehicle mobility. *IEEE Transactions on Control of Network Systems*. https://doi.org/10.1109/TCNS.2018.2809960.
71. Deilami, S., Masoum, A. S., Moses, P. S., & Masoum, M. A. S. (2011). Real-time coordination of plug-in electric vehicle charging in smart grids to minimize power losses and improve voltage profile. *IEEE Transactions on Smart Grid, 2*(3), 456–467.
72. Amini, M. H., Jamei, M., Lashway, C. R., Sarwat, A. I., Yen, K. K., Domijan, A., et al. (2015). Plug-in electric vehicle owner behavior study using fuzzy systems. *International Journal of Power and Energy Systems, 35*(2).

73. Clement-Nyns, K., Haesen, E., & Driesen, J. (2010). The impact of charging plug-in hybrid electric vehicles on a residential distribution grid. *IEEE Transactions on Power Systems, 25*(1), 371–380.
74. Mwasilu, F., Justo, J. J., Kim, E. K., Do, T. D., & Jung, J. W. (2014). Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. *Renewable and Sustainable Energy Reviews, 34*, 501–516.
75. Amini, M. H., Karabasoglu, O., Ilić, M. D., Boroojeni, K. G., & Iyengar, S. S. (2015). ARIMA-based demand forecasting method considering probabilistic model of electric vehicles' parking lots. In *Power & Energy Society General Meeting, 2015 IEEE* (pp. 1–5). Denver: IEEE.
76. Sovacool, B. K., Noel, L., Axsen, J., & Kempton, W. (2018). The neglected social dimensions to a vehicle-to-grid (V2G) transition: A critical and systematic review. *Environmental Research Letters, 13*(1), 013001.
77. Thomas, D., Deblecker, O., & Ioakimidis, C. S. (2018). Optimal operation of an energy management system for a grid-connected smart building considering photovoltaics' uncertainty and stochastic electric vehicles' driving schedule. *Applied Energy, 210*, 1188–1206.
78. Pirouzi, S., Aghaei, J., Vahidinasab, V., Niknam, T., & Khodaei, A. (2018). Robust linear architecture for active/reactive power scheduling of EV integrated smart distribution networks. *Electric Power Systems Research, 155*, 8–20.
79. Wang, S., Dong, Z. Y., Luo, F., Meng, K., & Zhang, Y. (2018). Stochastic collaborative planning of electric vehicle charging stations and power distribution system. *IEEE Transactions on Industrial Informatics, 14*(1), 321–331.
80. Ravichandran, A., Sirouspour, S., Malysz, P., & Emadi, A. (2018). A chance-constraints-based control strategy for microgrids with energy storage and integrated electric vehicles. *IEEE Transactions on Smart Grid, 9*(1), 346–359.
81. Abeywardana, D. B. W., Acuna, P., Hredzak, B., Aguilera, R. P., & Agelidis, V. G. (2018). Single-phase boost inverter-based electric vehicle charger with integrated vehicle to grid reactive power compensation. *IEEE Transactions on Power Electronics, 33*(4), 3462–3471.
82. Shi, Y., Tuan, H. D., Savkin, A. V., Duong, T. Q., & Poor, H. V. (2018). Model predictive control for smart grids with multiple electric-vehicle charging stations. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2017.2789333.
83. Nan, S., Zhou, M., & Li, G. (2018). Optimal residential community demand response scheduling in smart grid. *Applied Energy, 210*, 1280–1289.
84. Luo, C., Huang, Y.-F., & Gupta, V. (2018). Stochastic dynamic pricing for EV charging stations with renewable integration and energy storage. *IEEE Transactions on Smart Grid, 9*(2), 1494–1505.
85. Neyestani, N., et al. (2018). Effects of pev traffic flows on the operation of parking lots and charging stations. *IEEE Transactions on Smart Grid, 9*(2), 1521–1530.
86. Zhu, X., Xia, M., & Chiang, H.-D. (2018). Coordinated sectional droop charging control for EV aggregator enhancing frequency stability of microgrid with high penetration of renewable energy sources. *Applied Energy, 210*, 936–943.
87. Amini, M. H., Boroojeni, K. G., Wang, C. J., Nejadpak, A., Iyengar, S. S., & Karabasoglu, O. (2016). Effect of electric vehicle parking lots' charging demand as dispatchable loads on power systems loss. In *Electro Information Technology (EIT), 2016 IEEE International Conference on* (pp. 0499–0503). Grand Forks: IEEE.
88. Mohammadi, E., Fadaeinedjad, R., & Rashidinejad, M. (2018). Optimal placement and sizing of PV systems and electric parking lots considering reactive power capability and load variation. *International Journal of Sustainable Energy, 37*, 1–14. https://doi.org/10.1080/14786451.2018.1494597.
89. Kosmanos, D., Maglaras, L., Mavrovouniotis, M., Moschoyiannis, S., Argyriou, A., Maglaras, A., et al. (2018). Route optimization of electric vehicles based on dynamic wireless charging. *IEEE Access, 6*, 42551–42565.
90. Mohsenzadeh, A., Pazouki, S., Ardalan, S., & Haghifam, M.-R. (2017). Optimal placing and sizing of parking lots including different levels of charging stations in electric distribution networks. *International Journal of Ambient Energy*, 1–8.

91. Mohsenzadeh, A., Pang, C. Z., Pazouki, S., & Haghifam, M.-R. (2015). Optimal siting and sizing of electric vehicle public charging stations considering smart distribution network reliability. In *North American Power Symposium (NAPS), 2015* (pp. 1–6). Charlotte: IEEE.
92. Amini, M. H., & Islam, A. (2014, February). Allocation of electric vehicles' parking lots in distribution network. In *ISGT 2014* (pp. 1–5). Washington, DC: IEEE.
93. Sadati, S. M. B., Moshtagh, J., Shafie-khah, M., Rastgou, A., & Catalão, J. P. S. (2019). Operational scheduling of a smart distribution system considering electric vehicles parking lot: A bi-level approach. *International Journal of Electrical Power & Energy Systems, 105*, 159–178.
94. Lam, A. Y. S., Leung, K.-C., & Li, V. O. K. (2017). Vehicular energy network. *IEEE Transactions on Transportation Electrification, 3*(2), 392–404.
95. Lam, A. Y. S., Leung, K.-C., & Li, V. O. K. (2015). An electric-vehicle-based supplementary power delivery system. In *Smart Grid Communications (SmartGridComm), 2015 IEEE International Conference on* (pp. 307–312). Miami: IEEE.
96. Chen, X., Leung, K. C., Lam, A. Y., & Hill, D. J. (2017, December). A novel online scheduling algorithm for hierarchical vehicle-to-grid system. In *GLOBECOM 2017-2017 IEEE Global Communications Conference* (pp. 1–6). Singapore: IEEE.
97. Li, Y., Davis, C., Lukszo, Z., & Weijnen, M. (2016). Electric vehicle charging in China's power system: Energy, economic and environmental trade-offs and policy implications. *Applied Energy, 173*, 535–554.

Part I
Complex Networks: Theory and Real-World Applications

Chapter 3
Sustainable Smart Cities Through the Lens of Complex Interdependent Infrastructures: Panorama and State-of-the-art

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Introduction

Overview

Smart cities are developed to enable modern functionalities (e.g., sustainable energy systems, smart power grids, and electrified transportation networks) and focus on the information and communication technologies (ICTs) in order to improve the operation and efficiency of the future cities. Proper operation of the smart cities relies on a wide range of complex interdependent infrastructures. These critical infrastructures operate in a collaborative manner to improve the performance of this interconnected network of networks, which ultimately translates into enhancing quality of life for the citizens. The Internet of Things (IoT) is one of the key players for upgrading current urban areas to smart cities. Further, the concept of smart cities is developed to integrate smart technologies and solutions with the foremost goal of improving the quality of life. The advanced metering, control,

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information, and communication technologies are the backbones of smart cities that are utilized to gather and analyze the data in order to provide energy-efficient, cost-efficient, reliable, and secure services. Smart cities focus on the coordination between different sectors including energy and transportation systems, water supply networks, and healthcare in order to enable more efficient applications. This chapter aims to provide a review on the smart cities and the needs of sustainability for the future cities, as well as the ongoing challenges for smart city implementation. Furthermore, an overview is provided to explain the interdependent power and transportation networks, as one of the key elements of future smart cities. Regarding the applications of smart cities, increasing amount of information should be gathered from the cities and community via distributed sensors, as well as the control devices. Privacy and security issues will rise due to the concerns regarding the protection of the collected data and transmitted control signals against the malicious behaviors. Such issues are also covered in this chapter. Thus, although smart cities can benefit citizens in a variety of aspects, there are some privacy and security concerns regarding the possible data leakage and malicious attacks. To enhance the acceptability of the high penetration of smart cities and their real implementation potential, all the presented aspects are addressed.

The concepts of smart cities and sustainability have been focused worldwide due to their importance to satisfy the challenges of the future cities [1]. The concept of smart sustainable cities emerged in order to cope with the high rate of urbanization and ongoing issues (e.g., to provide the increasing electricity demand, reduce the emission rate, and decrease the use of fuel resources) [2]. The sustainability is a matter of actions in a multidimensional and multidisciplinary axis in each contemporary city to avoid the environmental impacts and face the climate change and the corresponding issues such as the increasing CO2 emissions. The initial idea of smart cities has been introduced in the literature [3–5]. Heng et al. [5] defined Singapore as an "intelligent city" in their study by focusing on the significance of telecommunication and information.

Kitchin [6, 7] defined smart cities as a concept that involves several stakeholders from areas such as academia, business, and government. In [6], smart cities are defined as a complex combination of efficient computational capacity, as well as emerging technologies that are motivated by economic benefits as well as social gains. Further, he discussed how smart cities are operating utilizing digital technologies to achieve sustainability, reliability, energy efficiency, and productivity. He also discussed the key role of big data to address these challenges that are categorized as the politics of big urban data; corporatization of city governance and a technological lock-in; buggy, brittle, and hackable cities; technocratic governance and city development; and panoptic city. In Kitchin [7], a big picture of smart cities and the corresponding concepts is depicted, which provides a general overview of entities and technologies in the smart cities. Kitchin et al. [8] investigated urban development in terms of providing the trend to upgrade the way that the cities are currently operated. In other words, they described how and to what ends indicator, benchmarking, and dashboard motivations can be deployed by cities to improve the overall performance of the cities. According to their study, although these motivations aim to promote the urban development to more transparent systems while ameliorating the decision-making procedure for entities in the city, the current methods for decision-making have the issue of insufficient information as well as technical challenges. Previous studies focused on the concept of smart cities from theoretical point of view. However, there is a crucial need for specifying stakeholders and their corresponding roles and benefits in the smart cities' framework. To this end, Coletta et al. [9] introduced practical smart city environment in Dublin, Ireland, and evaluated the interaction among four major authorities in this specific framework. Cardullo and Kitchin [10] mainly appraised the role of the citizens of smart cities in their living environment. They also presented the remedies to unveil the required approaches to frame the citizens from the smart cities' decision makers' perspective. Shelton et al. [11] deployed an evaluation of case studies in Louisville and Philadelphia, to illustrate the application of the policies in real-world cities, rather than conceptual smart city models. The advantage of their study is being adaptive to the available actual models.

Batty [12, 13] defines smart cities as a transition to improve the livability of cities in the twenty-first century. Batty [12] presented that there is a considerable gap between physical and social aspects of smart cities. Batty et al. [14] investigated novel approaches based on data analysis to perceive the concept of smart cities. To this end, they built on the large number of deployed sensors, which are being used to increase the observability of modern cities by providing valuable knowledge about the status of the network in a city. Calzada and Cobo [15] introduced the novel concept of unplugging, which according to them mainly refers to fundamentally assess the technological aspects of the smart cities. To this end, a conceptual framework is proposed to revisit the basic requirements of smart cities [15]. According to [16], empirical study based on real-wrold data presents that there is a general rule for processes relating urbanization to economic development. Further, according to [17], the urbanization rate was 30% by 1950; now, it reached more than 50% worldwide which shows the growing trend toward urbanizing the population.

The concept of the smart cities is to incorporate Information and communication technology (ICT) as well as the Internet of Things (IoT) in a secure way for the optimal operation of the existing assets (such as transportation network, healthcare (hospitals), power plants, and water supply systems) [18]. Mitchell [19] mentioned to the role of smart technologies (e.g., the telecommunication networks, sensors, and software) to enhance the smartness of the cities. Such technologies will appear by developing the idea of online communication using Internet, wireless sensor networks, the World Wide Web (WWW), smartphones, digital cameras, and global positioning system (GPS). The aim of smart cities is to enhance functionalities by using the novel technologies, i.e., the emerging technologies that expedite the transition towards smart cities (such as smart devices, smartphones, street cameras, sensors). The ICTs will provide the possibility to manage and monitor the city in order to improve the quality of life. By using the sensors and real-time monitoring systems, the data of the people and objects are gathered, processed, and analyzed to enhance the efficiency of the smart cities [20]. The mentioned data covers a wide range of measurements (e.g., smart metering infrastructure, GPS information of the mobile objects such as electric vehicles, healthcare device measurements), available data of citizens (e.g., personal identity, living habits), and historical information from various infrastructure (e.g., historical electricity demand profile, historical driving habits, historical weather information). For instance, if the data of driving patterns and traffic jams could be gathered and effectively analyzed, the transportation services can be planned better or the city development can be performed in a better way. ICT could improve the functionality of services, reduce the energy usage and total costs, and facilitate the communication among people and government [21].

The terms "smart cities" or alternatively intelligent cities are introduced to face with the increasing challenges in a cost-effective and environment-oriented manner [22]. Caves and Walshok in [23] and Caves in [24] addressed the digitalization as an important issue towards smart communities. Also, "intelligent cities" and "knowledge cities" are discussed in [25–27]. Different domains of local government (e.g., services and development policies) are investigated in [27]. Anttiroiko et al. [22] developed the idea of intelligent public services and the service economy is presented as a platform for the governments. This study provides a framework to comprehend the principles and applications of smart services. Komninos et al. [28] referred to the intelligent cities as a gradual forming of a planning scheme related to the expansion of sustainable cities and novel management system (i.e., upgraded management systems that are benefiting from modern information technologies to improve the required procedures). Regarding the technological perspective, smart cities focused on the advanced devices placed in the city to build modern systems [25, 29]. In order to explore novel applications and emerging services, EU research intends to understand the novel services on the basis of ICTs [30]. Yigitcanlar [30] investigated the effect of advanced technologies in the development of smart cities and also undertook a critical survey about smart cities' models. Lee et al. [31] and Yigitcanlar and Lee [32] investigated ICT-based technologies with an application in the smart cities.

Conspicuous concepts and features of smart cities are defined by Giffinger et al. in [33] and developed by Boyd Cohen in [34] through the introduced Smart Cities Wheel. According to [34], the main components of the smart cities are (1) smart people; (2) smart economy; (3) smart environment; (4) smart governance; (5) smart living; and (6) smart mobility. There are indicators to describe these components [35]. Boyd Cohen [34] provides a framework to understand the smart cities' classifications and elements. It contains the potential of all six components in the smart cities. The components of the Boyd Cohen's Smart Cities Wheel are shown in Fig. 3.1 [35]. It is worth noting that the Smart Cities Wheel is a start point to construct a framework for developing smart cities [35]. This framework has been developed to assess the smartness of the cities [36]. Other approaches have been presented to assess the performance of the smart cities [37–39]. Debnath et al. [40] have proposed special frameworks to evaluate the smartness of the cities based on their transportation networks. Garau et al. [41] proposed a method to evaluate the smart transportation system and employ it to assess several cities of Italy.

Smart cities are highly interested in recent years due to their ability to respond the upcoming urban requirements [1, 42]. The United Nations forecasted that until

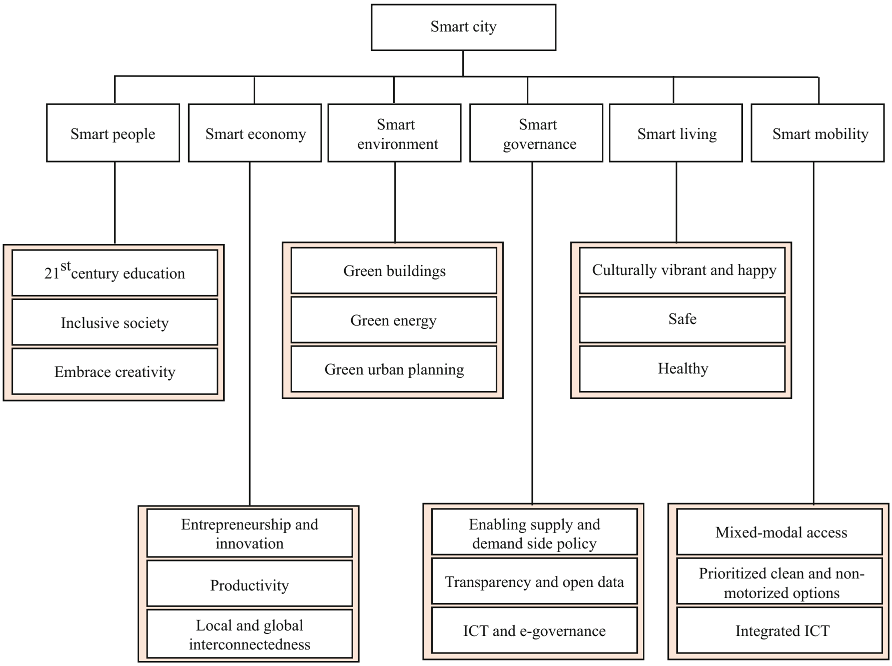

Fig. 3.1 The components of the Boyd Cohen's Smart Cities Wheel [35]

2050, 66% of the world's population will live in urban areas [43] that could have important environmental and social effects [44]. Since cities are major energy users (because of the density of residents in cities), the sustainable planning of cities is also focused to overcome the raising challenges. Therefore, the long-term plans should consider the sustainability of the cities in order to better satisfy the future requirements [45].

In addition, the growing urbanization raises many issues related to the rate of pollution, transportation network, resource reduction, community vulnerability, and people's well-being [1]. Therefore, it is necessary to provide innovative solutions and infrastructure to overcome the future problems. For this purpose, advanced metering and smart devices are used to enhance the efficiency of the smart cities' applications, such as transportation (by improving the traffic management activities), parking lots (by developing the parking lots based on the information about the arrival and departure patterns of cars), and environmental monitoring (by analyzing the accurate data about temperature, rain, and water level of lakes) [46–48]. Hence, emerging technologies and services are needed in order to satisfy the new requirements by citizen, such as a pivotal need for highly reliable power supply to maintain proper operation of digital devices. Many digital devices (such as sensors and actuators) are developed in response to the necessities of the smart cities that are able to be connected via Internet [49]. Small scale power grids, with the abiloity of grid-isolated operation without interruptions, are one of the solutions to increase the reliable power supply in the digital world [50, 51].

While by using the current Internet infrastructure people are connected with each other, the future revolution of the Internet will provide the possibility of the interconnection between devices. In 2011, the number of interconnected devices was more than the population of the cities [52, 53].

The IoT paradigm is based on the smart devices interconnected by using advance infrastructure. The IoT could be defined as distributed agents provided to enhance the reliability level and improve the functionality of the smart cities [53]. Here, the term agents is referred to smart elements (such as smartphones and sensing components) and other elements (such as tools, statues, landmark, and artist's work) that could work with each other for providing a specific goal (that the IoT is employed to provide it) [46, 54, 55]. A sample of interconnections based on the IoT is illustrated in Fig. 3.2 [46, 52]. Therefore, IoT has an important role in the different aspects of people's life (such as well-being, security, and transportation), as well as the policy targets (such as energy efficiency, needed infrastructure, and pollution reduction). Consequently, IoT is essential to provide more efficient, economic, and secure operation of the smart cities' systems (such as transportation and electrical systems) on the basis of various features, such as energy efficiency plans (strategies that are considered as the policies of the smart city development in order to decrease the energy consumption in different sectors such as residential, industrial, and agriculture), economical aspects, and reliability indices.

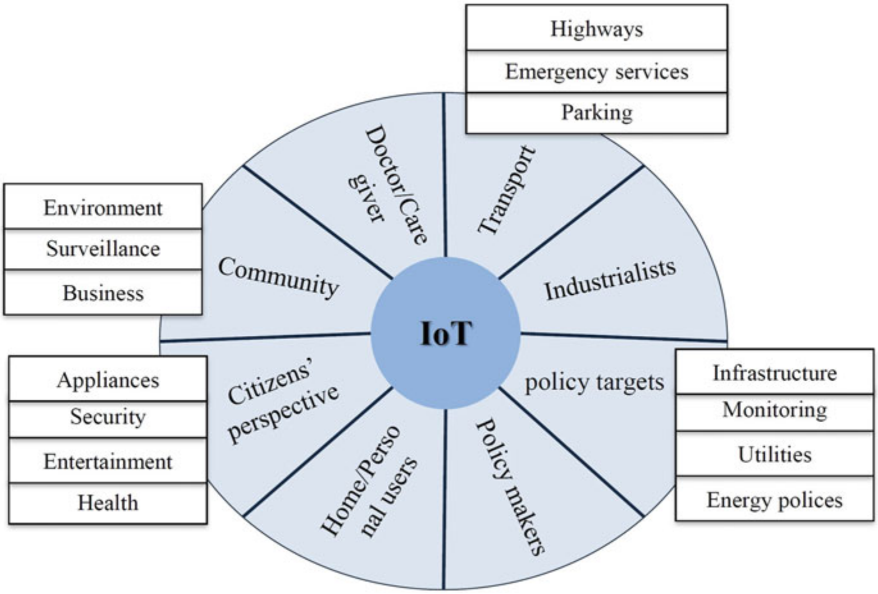

Fig. 3.2 Interconnections on the basis of the Internet of Things [46, 52]

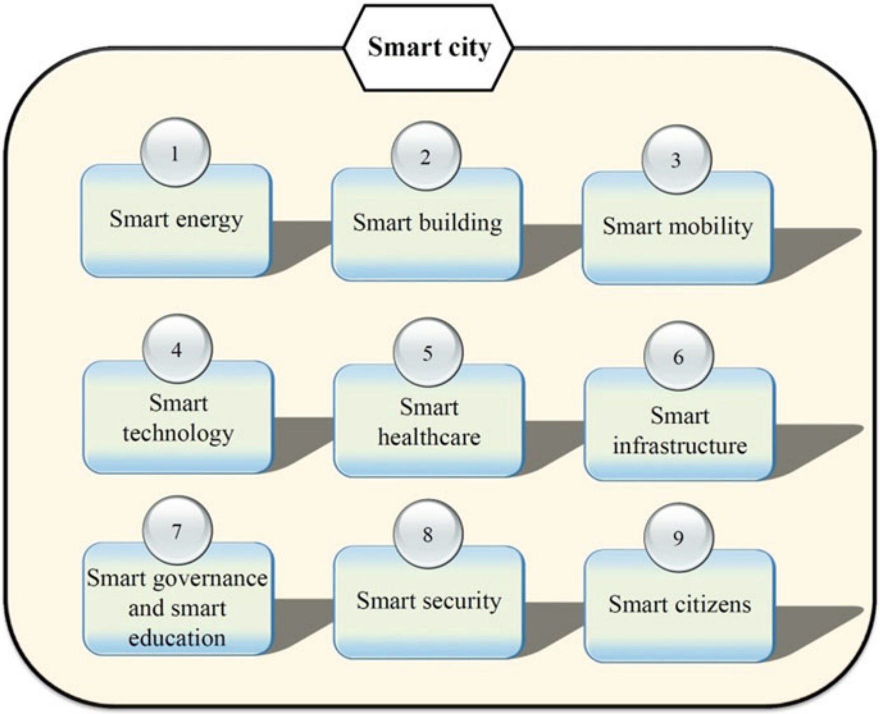

Fig. 3.3 The key features of the smart cities [46, 56]

Currently, cities are smarter than the past, because of the dramatic progresses of the digital technologies, and contain different aspects of life as shown by Fig. 3.3 [46, 56]. Modern smart devices (such as street cameras for monitoring systems, sensing devices for transportation networks, and advanced metering infrastructure in power and energy systems) are employed by the smart cities. On the basis of the IoT, objects could be incorporated regarding the geographical position and investigated through analyzing systems. Sensor services (to gather data) could be utilized with many schemes by the consideration of the behavior of cyclists, drivers, and public parking lots. The IoT infrastructure is employed with numerous service domain applications with the aim of facilitating the actions regarding the pollution reduction policies, transportation, and monitoring systems [46].

The aim of this review paper is to focus on the potential of smart cities (to improve the performance of services, make the cities to be more sustainable, and finally enhance the quality of life), as well as their main challenges and barriers. The ICTs and IoT are highly focused in this chapter as the backbones of smart cities. The common architecture of the smart cities to support the presented goals is introduced. It should be noted that, here, the meaning of the common architecture is the general view and functionalities of the cities that could be considered to lead the cities towards the smart ones. Also, some examples and definitions of the smart city architectures are presented in this section. Moreover, the applications of the smart cities in different domains (including energy, environment, industry, living, and services) are described. In addition, the interdependent power and transportation networks are investigated as an essential part of the smart cities. However, when the concept of smart cities and high utilization of smart technologies are being studied, the major concern is about the privacy and security (due to the high amount of data related to people's life, and control signals). Such issues may be the most important barrier for the high utilization of smart devices and the acceptance of people. Hence, based on the explained features and components, the chapter addresses the privacy and security issues as the main challenges of the smart cities' penetration level. The chapter is organized as follows. Section "Smart Sustainable City" presents the concept of smart sustainable cities and the role of advanced technologies in the sustainability of the cities. In order to introduce the architecture of the smart cities, as well as their applications in different domains (as introduced above), Sections "Smart Cities Architecture" and "Smart City Applications" are elaborated. Section "Interdependent Power and Transportation Networks in the Context of Smart Cities" addresses the interdependent power and transportation networks in the smart cities. In section "Interdependent Power and Transportation Networks in the Context of Smart Cities," the security and privacy problems of smart cities are discussed as the barriers of the high penetration of the smart cities' technologies. Finally, the conclusion remarks are drawn in section "Conclusion."

Smart Sustainable City

There are many efforts to define the concept of smart cities. The content analysis makes it possible to compare the definitions, visions, elements, and goals of the smart cities [2]. Although there are many definitions around the smart cities and sustainable city, the exploration of combined smart and sustainable city is difficult because of the multiplicity and variety of the presented definitions [2, 57]. According to [1], smart sustainable cities employ smart devices to provide the high quality of life, efficient operation and services, and competitiveness. Furthermore, it aims to overcome the requirements of the current and future systems. However, the economic, social, and environmental considerations should be met. The final goal is to develop more efficient and sustainable system. ICT is a key driver to cope with the challenges of sustainability and the development of the city. It offers significant contributions associated with such plans. In fact, a city is a smart sustainable, if smart ICTs are utilized to make them more sustainable [58]. The success of smart cities to overcome their problems by using the ICT (for instance, if the driving patterns could be analyzed by using the collected data, the traffic problem may be managed better to avoid heavy traffics and also the allocation of charging stations could be planned in an optimal way) shows the advantages of the smart cities as the urban planning policies. However, still it is necessary to provide researches to address the necessity, priorities, timeliness, and important issues of the current models of the smart sustainable city.

Sustainability is presented as one of the objectives in the future [25]. Energy saving, the utilization of different energy resources (e.g., wind generations and photovoltaic), the reduction of environmental pollution, and the preservation of ecosystems are introduced as the needs of this objective [59]. Smart cities are considered to cope with the upcoming challenges and provide the optimal solution. The concept of smart sustainable city is to converge the sustainable development, urbanization, and technological progress [58]. In order to obtain the multidimensional urban sustainability, people's behavior as well as governmental actions are changed to be more intensive towards this direction (for instance, Mexico City has a large metro, but it does not serve several places of the Mexico City metropolitan area). Therefore, the design patterns provide solutions to transportation problems, robust and flexible enough in unpredictable environments and sustainable to provide safe and economical access to citizens and locations to satisfy the environmental concerns and natural ecosystems [60, 61]. Practically, psychologists can have an important role to change human behavior towards the goals of smart sustainable cities [60, 62, 63]. McFarlane [64] conceptualized the learning on the basis of translation, coordination, and dwelling.

In the smart cities, the ICT can improve the citizens' access to the information and services [60]. High utilization of advanced ICT is a key feature of the smart sustainable cities that enables cities to be smarter and more sustainable and enhances the quality of life. Hence, cities can be remained sustainable by employing ICTs to cope with rapid urban development and the corresponding changes. Since cities are complex systems, their development towards sustainable cities demands modern technologies provided by ICTs [65–67]. Therefore, ICTs have an essential effect in the sustainability of the cities and offer new ways to understand and address the existing issues [68]. So, the aim of smart sustainable city is to achieve an optimal solution of using the smart technologies to address the aims of the sustainable development (generally, sustainability is a relation among people and their surrounding environment to ensure that the people requirements are satisfied in both short-term and long-term horizons; hence, the term "sustainable development" indicates that the human requirements are met at present and future [69, 70]). It is worth mentioning that ICTs can be deployed to optimize the energy consumption by improving activities such as plant watering and monitoring of buildings to manage the appliances in an optimal manner [71]. In agriculture, ICTs could be utilized to minimize the amount of wastewater (smart sensors could detect and measure useful information such as the soil moisture to improve the irrigation) [72]. Hence, the comprehension of the ICTs' effects on the sustainability can lead towards the optimum use of new technologies to obtain relevant benefits.

It is worth noting that the sustainable development has three aspects: society, environment, and economic aspects. Each society will benefit from a sustainable development by having access to more efficient services with lower costs and improving the social welfare. Further, it reduces the air pollutions and greenhouse gases and paves the way towards green environment. Last but not least, sustainability has an economic aspect, which refers to optimizing the operation cost of the infrastructure in smart cities by deploying efficient computational algorithms.

The existing models of smart cities still have many issues regarding the applicability. Hence, more novel approaches are required in order to cope with these problems. The ICT could have a key role to address these issues. Current smart city projects highly rely on ICT as the main component to design and construct smart cities [73]. In the context of smart cities' development, the ICT denotes the set of urban infrastructure, architectures, applications, systems, and other smart devices. Such elements are developed to handle different tasks like sensing, processing, analyzing, and managing the information in order to monitor and plan modern cities. The purpose of ICT implementation is to improve the management and functionality of the system [1].

Technically, the urban ICT contains hardware components (e.g., sensors, Internet infrastructure, and database systems) and software elements (including software applications, big data analytics methods, decision-making systems, communication, and networking protocols) [1].

A deep investigation is needed to realize the effect of the ICT in the smart cities, and citizen health as well as quality of life. Such influences could be categorized in two major groups [2]:

The Role of ICT in Smart Cities' Applications

It contains the importance of the ICT to provide the leading technologies in smart city schemes as well as the effectiveness of the ICT as the asset of widespread and supporting technologies related to the different domains of the smart cities (e.g., smart transportation and energy systems) [2].

The Role of ICT on the Smart Cities' Well-Being

It describes the role of ICT to generate public and individual tools, artifacts, or services in order to improve the living of the citizens of the smart cities, and to provide profits and a higher well-being. This may be considered as the main aim of the smart cities that could bring many benefits to the citizens such as the reduction of the pollution (environmental benefits), reduction of traffic congestions (it can improve the quality of life), and providing of higher well-being.

However, the real effectiveness of ICT to provide public value in smart cities depends on the strategic plan to connect smart cities with ICT. The cities' readiness, and the people's intensity of use, as well as the effect of the ICT on the quality of life, is taken into account to evaluate the real potential of ICT-based smart projects. Hence, these investigations are necessary to ensure about the results of the smart cities' implementation for enhancing the quality of life [2].

Smart City Architecture

The smart city architecture is able to use the high amount of gathered data to exploit and analyze it in order to make the optimal decisions [74]. The architecture of the smart cities has been investigated by previous studies. Wenge et al. [75] proposed an architecture based on the data viewpoint. On the basis of human-system communication, a pyramid architecture is introduced in [76]. The first layer is named "smart infrastructure" containing several networks (electrical, gas, water, and communication). The next level is referred to as intelligent data storage consisting of servers to store the data, completing data storage units. Layer three is intelligent residential energy management system including automated control systems. Layer four is called the intelligent interface that includes integrated online platform. The fifth layer of the pyramid is the "smart cities" that should combine and integrate other layers [74, 75]. Anthopoulos and Fitsilis [77] proposed a five-layer generic architecture based on the logical and physical perspectives. Krylovskiy et al. [78] presented a comprehensive framework, referred to as the DIMMER system. This system interacts with building information as well as power utility companies to integrate the real-time data from distributed sensors installed at the power network and building layers. They further introduced the DIMMER Smart City project that aims to construct a platform and some additional applications to involve stakeholders to ameliorate the energy efficiency in future cities [78]. According to their proposed service platform for smart cities, there are three crucial district information models: geographic information systems (GIS) and building information models (BIM), and system information models (SIM). Here, the concepts of BIM and GIS, and their role in smart city development, have been investigated. According to Liu et al. [79], on the one hand BIM represents the digital representation of the physical and functional features of a facility in building. On the other hand, GIS is introduced to control and evaluate spatial data based on geographically labeled information. Although GIS enables spatial analysis at the large-scale outdoor applications, it suffers from a detailed knowledge regarding the buildings and indoor information [79]. To tackle this issue, Liu et al. proposed to deploy BIM systems that provide the system operators with elaborated and accurate information about each application in the building, including pipeline networks. Further, Tan et al. [80] deployed BIM technology and improved A* approach to minimize the lift path for offshore oil and gas platforms during disassembly. According to them, BIM provides accurate component-based geometric data that can be leveraged for improving the lift path optimization problem. In a related context, Soto et al. [81] presented a smart city platform, referred to as ALMANAC, as an effective solution to take the existing services, sensors, and infrastructure into account. According to their study, it is inevitable to consider stakeholders with their own objectives and requirements while collecting and analyzing the data for the smart city applications. Lohan et al. [82] identified the role of location-based services in smart cities' context. To this end, they provide a thorough and inclusive overview of the issues and solutions regarding the collection, storage, analysis, and visualization of the movement data of moving people in the smart cities. They also outlined the potential applications of user movement data in the following three contexts: smart cities, IoT, and Internet of People (IoP). A comprehensive review of BIM concept is provided by Volk et al. [83]. According to their review of over recent 180 publications on the BIM, BIM utilization in the current buildings introduces three key challenges: high modeling requirement from collected building information into semantic BIM objects, converting the data to integrate and deploy into the BIM platform, and handling the stochastic nature of data in existing buildings. Zdraveski et al. [84] developed an ICT infrastructure on the basis of the ISO 37120 standard in order to integrate data (from numerous sensors, and social networks, as well as other data sources) with the aim of creating a context-aware and energy-efficient IoT/big data/cloud platform. However, due to the complexity of the smart city infrastructure, more explorations are needed to provide architectural patterns/designs to support smart cities' services (that support and make it possible to provide smart city services).

Smart cities employ sensing components, heterogeneous networks, and processing units, as well as control and operating elements, and are able to gather and utilize the data that is obtained from the physical world, transferred through the communication world, and processed in the information world to provide efficient services [85]. These components are briefly described in the following.

1. Sensing components: Smart components contain different smart devices (including sensing elements, smartphones, smart meters, and video surveillance cameras) for measuring data from the physical world and submit them to the processing units [86]. It is noteworthy that, because of some constraints of these devices (including their sizes, batteries, and processing abilities), such components often process or compress the real-time and granular data at first, and then send it to the network [85].
2. Heterogeneous networks: The heterogeneous networks are the connections between the physical and information worlds (communication world). They have a key role to support the sensors and applications in order to collect the sensed information [33]. It incorporates cellular networks, wireless local area networks, wide area networks, device-to-device communications, millimeter-wave communications, and sensor networks, and enables seamless switching between systems [85].
3. Processing unit: The analyzing and processing of the sensed data from the physical world are handled by the processing unit that employs powerful cloud computing servers, numerous databases, and special control systems to manage the information world. The processing units manage the information worlds of the smart cities. Entities have the specific authorizations to access the data and are able to specify the strategies for decision-making and control in the smart cities [85].
4. Control and operating elements: The control and operating components are employed to handle the physical world by using the corresponding devices (including servo actuators, smartphones). Such components adjust the physical

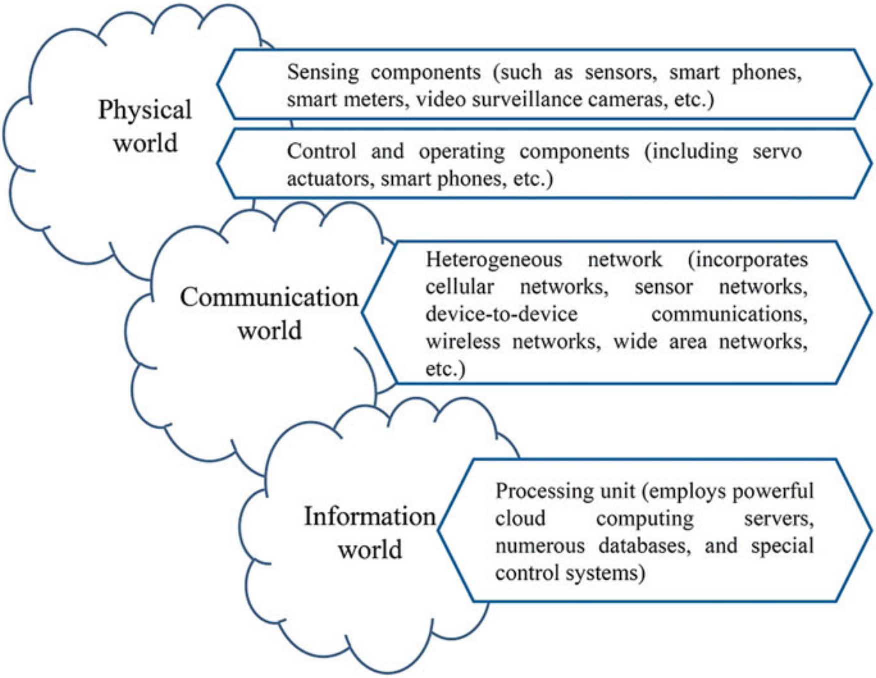

Fig. 3.4 The architecture of the smart cities [85]

world to provide a high-quality life. For instance, in the transportation network, reducing the traffic congestion will enhance the quality of life. Furthermore, they employ the relevant devices to have the knowledge regarding the physical world, and monitor and manage the components to smartly operate the system [85].

Figure 3.4 schematically illustrates the introduced architecture of the smart cities [85].

As the physical and information worlds are connected together through the smart cities, numerous intelligent applications could be enabled. The next section is provided to highlight such new application.

Smart City Applications

Future smart cities will provide novel information technologies and communication infrastructure, which enable more efficient control and optimization of available resources. In this context, smart power grid and its corresponding technologies are evolving as a dynamical complex system that can take advantage of emerging resources in smart cities to improve its optimal operation [87]. Karnouskos et al.

[87] provided a comprehensive JADE-based simulator that analyzed, designed, and built on software agents to elaborately model the dynamic behavior of a smart city and its agents, including smart grids and electrified transportation networks. Their main focus was on the power grid as a pioneer towards upgrading its available technologies to more intelligent, efficient, and reliable ones to boost the energy efficiency. Moreover, Morvaj et al. [88] described smart houses, as pivotal parts of smart grids, with four major characteristics: (1) demand-side management and demand response, (2) small-scale renewable energy resources (e.g., rooftop solar panels), (3) small-scale energy storage units, and (4) local controller for energy price optimization (see [89, 90] for more details on demand response, load management). In their framework, smart houses are responsive to the price signals from the power grid to adjust their consumption in an optimal manner. Smart power grids are introduced at different levels including transmission networks modernization and smart distribution networks. Some studies developed game theoretic frameworks to study smart grids [91–93].

Different applications are introduced for the smart cities that could provide benefits in the related domains including energy, environment, industry, living, and services [85]. These applications are briefly introduced in the following.

Smart energy: High utilization of smart devices and sensors will make it possible to monitor the energy delivery-chain systems, reduce the energy consumption, and prevent the failures of energy systems and blackout of the power systems [94].

Smart environment: The utilization of widespread sensors as well as smart climate management; different environmental issues such as waste gas, greenhouse gas, and city noise, air, and water pollution; and conditions of the forests could be monitored to provide the smart and sustainable planning of smart cities [86].

Smart industry: One of the aims of smart cities is the sustainable development of industrial sections. In this regard, the optimum generation and manufacturing are focused as well as the efficiency and robustness of the industries. Smart industries will limit the consumption of materials (for instance in the production lines) and resources (for instance labors and times), avoid the waste of energy, and so prevent the high value of emission. The sensors and control devices demand online feedbacks and accurate actions. Hence, all the components of smart industries are able to provide accurate controls [85].

Smart living: Smart living means the effective management of appliances in order to enhance the energy efficiency level and provide a comfortable home [95]. Smart devices in home areas can activate the remote control of home appliances, temperature modification, and energy saving. Furthermore, smart living can offer intelligent management of waste recycling, social networking, and parking for providing the smarter communities with pleasant lives, satisfying services, and sustainable environment [85].

Smart services: Smart services contain numerous public facilities and services to benefit the citizens (such as smart transportation to prevent the congestion of road traffic, smart healthcare to continuously control the health of the smart cities' citizens) [85, 96–98]. Clough and Casey [99] have defined mHealth as the utilization of mobile technologies to provide healthcare that could enhance the patient's

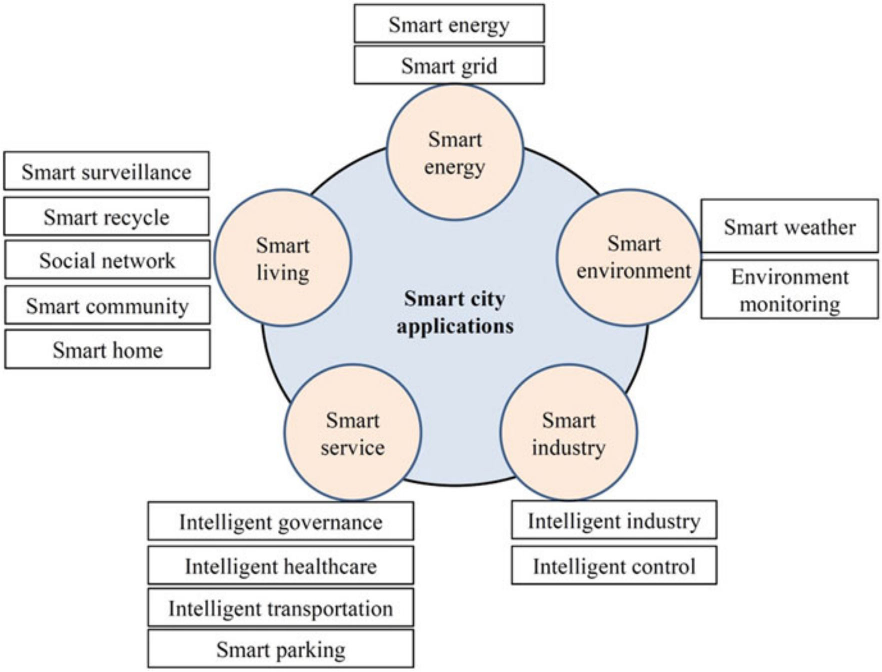

Fig. 3.5 Smart cities' applications [85]

access and engagement in psychological therapy. In recent years, the utilization of smartphones in psychotherapy as one of the expanding fields is examined [99].

Fig. 3.5 illustrates the introduced applications of smart cities [85]. As this figure shows, smart cities cover a wide range of application from the end users to the large-scale applications such as smart power grids and intelligent governments.

Interdependent Power and Transportation Networks in the Context of Smart Cities

Future power systems, referred to as smart grids, and electrified transportation networks are coupled through electric vehicle (EV) charging demand [100]. Due to the increasing charging demand of EVs, large-scale integration of EVs has been a challenging task for power system operators as well as transportation network operators [100]. From a general perspective, EV integration will increase the stochastic nature of load demand [101–103]. However, interdependent power and transportation network operators can leverage the flexible nature of this demand to ameliorate the reliability of the corresponding networks [104]. From the power system operator's perspective, flexible EV demand can be deployed for frequency control applications, ancillary service, loss minimization, peak shaving, and demand-side management strategies [105]. From the transportation network point of view, EV drivers can reduce their charging cost by using optimal strategies based on the provided incentives from the power system operator. For instance, a smart routing algorithm is proposed in [104] that not only takes the traffic conditions, driver's priorities, and charging station locations into account, but also considers the charging electricity price while finding the optimal route between the starting point and destination. Amini and Karabasoglu [104] have introduced a simulation platform to investigate the effectiveness of this approach based on IEEE standard test system for power network as well as a part of Shanghai transportation network for the routing evaluation. According to Viswanath and Farid [106], transportation electrification can be studied as a hybrid dynamic system. One of the major challenges of integrating EVs into future smart cities is to allocate the charging stations and renewable resources simultaneously [107, 108]. Weak emergence are those emergent properties that are only accessible through direct computer simulations (see [109] for an example of such a weak emergent phenomena).

Hence, another player in smart grids is the electrified transportation network. Recently, there has been a number of studies on developing efficient methods to address energy management concerns [110], enable advance sensing [111], and accommodate the electrified vehicles into power systems in terms of optimal EV scheduling [112, 113], mobile cloud computing for vehicular technologies (such as electric vehicles) in smart cities [114], and smart infrastructure design for smart cities while integrating intelligent transportation networks and smart grids [115]. Kamienski et al. [110] presented an Internet of Things-based framework to implement energy management in smart cities. Further, Cerna et al. [112] proposed mixed integer linear programming (MILP) approach to minimize the maintenance costs and extra hours to schedule a group of electric vehicles (EVs), considering the routing constraints along the path from starting point to destination. Mazza et al. [114] proposed biased randomized algorithm to achieve efficient and fast link selection with the application in mobile devices operated in a smart city platform.

Security and Privacy

Overall Descriptions

In the smart cities' environment, there are some privacy and security issues such as malicious attacks that could disrupt the operation of the smart devices and damage the quality of their services. A notable example of the requirement for secure operation is ensuring power networks resilience. In [116] a comprehensive overview of this concept is provided. Further, an overview of security and privacy issues in modern pwoer systems is provided in [117]. Moreover, the numerous existing photos and videos in a smart city, and the collected data of smart homes, may disclose the lifestyle of the customers. Such problems are related to the ethical issues. Malicious attackers may use this data and violate the privacy of the residents [118]. For instance, they may have access to the data of the people and disclose private images, videos, etc. Moreover, by using the data mining investigations, malicious attackers may recognize the typical behavior of citizens (such as the departure or arrival times) that could affect the citizens' life. Therefore, without suitable protections against privacy and security issues, residents may not accept the smart cities' penetration.

Indeed, the smart cities should protect the collected data from illegal access to ensure the security and privacy of the smart cities. A smart city gathers the data of the citizens' health as well as their environment, processes it, and affects the citizens' lives. Hence, because of these special features, security and privacy are puzzling concerns that could be considered as the barriers of the smart cities' penetration level. Privacy leakage, secure data storage and processing, as well as dependability in control are some important issues [85].

1. Privacy leakage

   Due to the collection, transmission, and process of private information in the smart cities, the private leakage may disclose people's identity, location, and lifestyle and make the smart cities vulnerable against the malicious attacks. To keep the privacy of the users, suitable methods (that are able to guarantee the privacy) are employed (e.g., encryption, anonymity, and access control) [119, 120]. An efficient protection mechanism is able to cope with the outside attackers as well as the inside attackers (like agents, employees, and security members, who have access to the data) [119]. Furthermore, due to the various types of the data (as above-mentioned) in the smart cities, the protection scheme is adjustable enough to keep the privacy and security [85].
2. Secure data storage and processing

   Since the storage and processing of the information are handled by using the cloud servers, they may face security dangers because of the unreliable servers [121]. One of the methods to cope with these types of threats is to encode the data to prevent the direct access to the untrusted cloud servers to it [52]. However, the cloud servers are not able to analyze the encoded data and perform impressive analytical operations for smart cities' applications [85].

   In addition, there are other security concerns related to the data sharing and access control (such as transportation data) that is difficult to provide the access procedure and support protected data sharing between the agents [85].

   Hence, the privacy and security threats in the storage and processing of the data of the smart cities need vast investigations.
3. Control dependability

   The control systems of the smart cities could be considered as the attractive objectives by the malicious attackers [122]. The operation and control functionalities of the smart cities could be affected by such attacks. Although the dependability of control is investigated by some studies [85, 123], the efficient and fast detection of malicious attacks and the malfunction of the control systems require extensive researches [85].

Conclusion

This chapter aims to expedite the collaboration of different parts [as prementioned, such as transportation network and healthcare (hospitals)] in order to develop and manage the sustainable and smart cities containing smart technologies. The concept of smart cities is a multidisciplinary science that attracted high attention in recent years due to its potential to affect various domains (such as energy, environment, and industry) to overcome the upcoming issues (like urbanization and limitations of fuel resources) and improve the quality of citizens' life. Smart cities leverage the interdependencies among several networks, such as power systems, transportation networks, healthcare, energy systems, and societal networks, to improve the social welfare, upgrade the current cities to more environmentally friendly cities, and minimize the system operation cost of these networks. In this chapter, the concept of emerging smart and sustainable cities is addressed and the key characteristics are thoroughly categorized. Furthermore, the architecture of smart cities that supports the connection of above-mentioned domains is introduced. Then, the corresponding applications are described to highlight the pivotal advantages of the smart cities as well as their main components. Although ICT is introduced as the key element of smart cities, the real capacity of these technologies depends on the strategies that connect the results with people's health and social welfare (that is the ultimate goal of smart cities' implementation). Moreover, an overview of the interdependent power and transportation networks as one of the key elements of future smart cities is provided. We also conclude that due to the large volume of collected data via real-time measurements from the people, community, and control systems, there is an exigent requirement for big data analysis methods to manage the smart cities properly. Future research can be performed in three major directions:

- Optimizing the operation of smart cities while taking the interdependencies among the existing infrastructure, such as water networks, energy systems, and communication network.
- Proposing an efficient optimization algorithm that is capable of handling the large-scale cost minimization, emission reduction, or social welfare maximization problems.
- Developing a new model for smart cities considering the emerging technologies in the elements of smart cities, such as smart measurement units in power systems, electrified vehicles in transportation networks, and accurate behavioral model of citizens.

References

1. Bibri, S. E., & Krogstie, J. (2017). Smart sustainable cities of the future: An extensive interdisciplinary literature review. *Sustainable Cities and Society, 31*, 183–212.
2. Dameri, R. P. (2017). *Smart city implementation*. Berlin: Springer International Publishing.

3. Gibson, D. V., Kozmetsky, G., & Smilor, R. W. (Eds.). (1992). *The technopolis phenomenon: Smart cities, fast systems, global networks*. New York: Rowman & Littlefield.
4. Schaffers, H., Komninos, N., Pallot, M., Trousse, B., Nilsson, M., & Oliveira, A. (2011). Smart cities and the future internet: Towards cooperation frameworks for open innovation. In J. Domingue et al. (Eds.), *The future internet. FIA 2011. Lecture notes in computer science* (Vol. 6656). Berlin, Heidelberg: Springer.
5. Heng, T. M., & Low, L. (1993). The intelligent city: Singapore achieving the next lap: Practitoners forum. *Technology Analysis & Strategic Management, 5*(2), 187–202.
6. Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal, 79*(1), 1–14.
7. Kitchin, R. (2015). Making sense of smart cities: Addressing present shortcomings. *Cambridge Journal of Regions, Economy and Society, 8*(1), 131–136.
8. Kitchin, R., Lauriault, T. P., & McArdle, G. (2015). Knowing and governing cities through urban indicators, city benchmarking and real-time dashboards. *Regional Studies, Regional Science, 2*(1), 6–28.
9. Coletta, C., Heaphy, L., & Kitchin, R. (2017). *From accidental to articulated smart city: The creation and work of Smart Dublin.* The Programmable City Working Paper 28, socarxiv. Available from https://doi.org/10.1177/0969776418785214.
10. Cardullo, P., & Kitchin, R. (2018). Being a "citizen" in the smart city: Up and down the scaffold of smart citizen participation in Dublin, Ireland. *GeoJournal*, 1–13. https://doi.org/10.1007/s10708-018-9845-8.
11. Shelton, T., Zook, M., & Wiig, A. (2015). The 'actually existing smart city'. *Cambridge Journal of Regions, Economy and Society, 8*(1), 13–25.
12. Batty, M. (2017). The age of the smart city. Centre for advanced spatial analysis (CASA) University College London.
13. Batty, M. (2015). Cities in a completely urbanised world. *Environment and Planning B: Planning and Design, 42*, 381–383.
14. Batty, M., Hudson-Smith, A., Hugel, S., & Roumpani, F. (2015). Visualising data for smart cities. In *Handbook of research on social, economic, and environmental sustainability in the development of smart cities* (Vol. 339). Hershey: IGI Global.
15. Calzada, I., & Cobo, C. (2015). Unplugging: Deconstructing the smart city. *Journal of Urban Technology, 22*(1), 23–43.
16. Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences, 104*(17), 7301–7306.
17. Bettencourt, L., & West, G. (2010). A unified theory of urban living. *Nature, 467*(7318), 912.
18. DimitrisKaradimas, A. P., Gialelis, J., & Koubias S. (2016). An integrated node for smart-city applications based on active RFID tags; Use case on waste-bins. *IEEE 21st International Conference on Emerging Technologies and Factory Automation (ETFA)*, 6–9 Sept. 2016, Berlin, Germany.
19. Mitchell, W. (2007) *'Intelligent cities', Inaugural Lecture of the UOC 2007–2008 Academic Year*. Available at http://www.uoc.edu/uocpapers/5/dt/eng/mitchell.html.
20. Musa S. (2016, January). Smart City Roadmap. [Online]. Available www.academia.edu/21181336/Smart_City_Roadmap.
21. Building a Smart City (2015), Equitable City–NYC Forward https://www1.nyc.gov/assets/forward/documents/NYC-Smart-Equitable-City-Final.pdf.
22. Ari-VeikkoAnttiroiko, P. V., & Bailey, S. J. (2014, August). Smart cities in the new service economy: Building platforms for smart services. *AI & Society, 29*(3), 323–334. https://doi.org/10.1007/s00146-013-0464-0.
23. Caves, R., & Walshok M. (1997). Transforming regions through information technology developing smart counties in California. *Calif County Mag* (pp. 29–31).
24. Caves, R. W. (2004). Responding to the information needs of citizens in an open society: The role of smart communities. *eTransformation in governance: New directions in government and politics* (pp. 216–233).

25. Komninos, N. (2002). *Intelligent cities: Innovation, knowledge systems and digital spaces*. London: Taylor & Francis.
26. Komakech, D. (2005). Achieving more intelligent cities. *Proceedings of the Institution of Civil Engineers-Municipal Engineer* (Vol. 158. No. 4), Thomas Telford Ltd.
27. Carrillo, F. J. (Ed.). (2006). *Knowledge cities: Approaches, experiences and perspectives*. London: Routledge.
28. Komninos, N. (2009). Intelligent cities: Towards interactive and global innovation environments. *International Journal of Innovation and Regional Development, 1*(4), 337–355.
29. Komninos, N. (2008). *Intelligent cities and globalisation of innovation networks*. London: Routledge.
30. Tan, Y. (2015). Smart cities: An effective urban development and management model? *Australian Planner, 52*(1), 27–34. https://doi.org/10.1080/07293682.2015.1019752.
31. Lee, S., Yigitcanlar, T., Han, H., & Leem, Y. (2008). Ubiquitous urban infrastructure: Infrastructure planning and development in Korea. *Innovation: Management, Policy and Practice, 10*, 282–292. https://doi.org/10.5172/impp.453.10.2-3.282.
32. Yigitcanlar, T., & Lee, S. (2014). Korean ubiquitous-ecocity: A smart-sustainable urban form or a branding hoax? *Technological Forecasting and Social Change, 89*(1), 100–114. https://doi.org/10.1016/j.techfore.2013.08.034.
33. Giffinger, R., Fertner, C., Kramar, H., Kalasek, R., Pichler-Milanovic, N., &Meijers, E. (2007). *Smart cities—ranking of European medium-sized cities*. Final Report, Vienna. Retrieved from: http://www.smart-cities.eu/download/smart_cities_final_report.pdf.
34. Cohen, B. (2012). What exactly is a Smart City? Fast CoExist. Retrieved Sept 13, 2015 from http://www.fastcoexist.com/1680538/what-exactly-is-a-smart-city.
35. Vinod Kumar, T. M. (2017). *Smart economy in smart cities*. Singapore: Springer Nature Singapore Pte Ltd..
36. Ahvenniemi, H., Huovila, A., Pinto-Seppä, I., & Airaksinen, M. (2017). What are the differences between sustainable and smart cities? *Cities, 60*, 234–245.
37. Albino, V., Berardi, U., & Dangelico, R. (2015). Smart cities: Definitions, dimensions, performance, and initiatives. *Journal of Urban Technology, 22*(1), 3–21. https://doi.org/10.1080/10630732.2014.942092.
38. Lazaroiu, G., & Roscia, M. (2012). Definition methodology for the smart cities model. *Energy, 47*(1), 326–332.
39. Lombardi, P., Giordano, S., Farouh, H., & Yousef, W. (2012). Modelling the smart city performance. *Innovation: The European Journal of Social Science Research, 25*(2), 137–149.
40. Debnath, A. K., Chin, H. C., Haque, M., & Yuen, B. (2014). A methodological framework for benchmarking smart transport cities. *Cities, 37*, 47–56. https://doi.org/10.1016/j.cities.2013.11.004.
41. Garau, C., Masala, F., & Pinna, F. (2015). *Benchmarking smart urban mobility: A study of Italian cities. Computational science and its applications—ICCSA 2015* (pp. 612–623). Switzerland: Springer International Publishing.
42. Hall, P. (1988). *Cities of tomorrow*. Hoboken: Blackwell Publishers.
43. World urbanization prospects. The 2014 revision. New York: Department of Economic and Social Affairs. Retrieved January 22, 2017 from http://esa.un.org/unpd/wup/Publications/Files/WUP2014-Report.pdf.
44. OECD environmental outlook to 2050. The consequences of inaction. OECD Publishing. Retrieved February 11, 2017. http://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/internationellt-miljoarbete/multilateralt/oecd/outolook-2050-oecd.pdf.
45. Bulkeley, H., & Betsill, M. M. Rethinking sustainable cities: Multilevel governance and the urban politics of climate change. *Environmental Politics, 14*(1), 42–63.
46. Arasteh, H., Hosseinnezhad, V., Loia, V., Tommasetti, A., Troisi, O., Shafie-Khah, M., Siano, P. (2016). IoT-based smart cities: A survey. *16 IEEE International Conference on Environment and Electrical Engineering (EEEIC)*, Florence, Italy, 7–10 June, 2016.
47. Botta, A., de Donato, W., Persico, V., & Pescapé, A. (2016). Integration of cloud computing and internet of things: A survey. *Future Genereration Computing Systems, 56*, 684–700.

48. Yazdani-Damavandi, M., Moghaddam, M. P., Haghifam, M. R., Shafie-khah, M., & Catalão, J. P. S. (2016). Modeling operational behavior ofPlug-in electric vehicles' parking lot in multienergy systems. *IEEE Transactions on Smart Grid, 7*, 124–135.
49. Rathore, M. M., Ahmad, A., Paul, A., & Rho, S. (2016). *Urban planning and building smart cities based on the internet of things using big data analytics* (Vol. 101, p. 63). Computer Networks. https://doi.org/10.1016/j.comnet.2015.12.023.
50. Lasseter, Robert H. (2002). Microgrids. In *Power Engineering Society Winter Meeting* (Vol. 1, pp. 305–308), IEEE. IEEE.
51. Amini, M. H., Boroojeni, K. G., Dragičević, T., Nejadpak, A., Iyengar, S. S. & Blaabjerg, F. (2017). A comprehensive cloud-based real-time simulation framework for oblivious power routing in clusters of DC microgrids. In *2017 IEEE Second International Conference on DC Microgrids (ICDCM)*. IEEE.
52. Gubbi, J., Buyya, R., Marusic, S., & Palaniswami, M. (2013). Internet of things (IoT): A vision, architectural elements, and future directions. *Future Genereation Computer Systems, 29*, 1645–1660.
53. Cao, H., Leung, V., Chow, C., & Chan, H. (2009). Enabling technologies for wireless body area networks: A survey and outlook. *IEEE Communications Magazine, 47*(12), 84–93.
54. Six technologies with potential impacts on us interests out to 2025. Disruptive civil technologies, 2008.
55. Alamri, A., Ansari, W. S., Hassan, M. M., Hossain, M. S., Alelaiwi, A., & Hossain, M. A. (2013). A survey on sensor-cloud: Architecture, applications, and approaches. *International Journal of Distributed Sensor Networks, 2013*, 1–18.
56. Strategic opportunity analysis of the global smart city market. http://www.egr.msu.edu/~aesc310-web/resources/SmartCities/Smart%20City%20Market%20Report%202.pdf.
57. Jenks, M. (2000). *Achieving sustainable urban form*. London: Taylor & Francis.
58. Höjer, M., & Wangel, S. (2015). Smart sustainable cities: Definition and challenges. In L. Hilty & B. Aebischer (Eds.), *ICT innovations for sustainability* (pp. 333–349). Berlin: Springer-Verlag.
59. Komninos, N. (2011, June 30). *What makes cities smart?* SC Conference, Edinburgh.
60. Khansari, N., Mostashari, A., & Mansouri, M. (2014). Impacting sustainable behavior and planning in smart city. *International Journal of Sustainable Land Use and Urban Planning (IJSLUP), 1*(2).
61. Cutcher-Gershenfeld, J., Field, F., Hall, R., Kirchain, R., Marks, D., Oye, K., et al. (2004). Sustainability as an organizing design principle for large-scale engineering systems. In *Engineering systems monograph* (pp. 5–42). Cambridge, MA: Massachusetts Institute of Technology.
62. Oskamp, S. (2000). A sustainable future for humanity? How can psychology help? *American Psychologist, 55*(5), 496–508.
63. Vlek, C., & Steg, L. (2007). Human behavior and environmental sustainability: Problems, driving forces, and research topics. *Journal of Social Issues, 63*(1), 119.
64. Learning the city: Knowledge and translocal assemblage C McFarlane. (2011). Books. google.com.
65. Colldahl, C., Frey, S., & Kelemen, J. E. (2013). Smart cities: Strategic sustainable development for an urbanworld. *Master Thesis, School of Engineering*, Blekinge Institute of Technology.
66. Kramers, A., Höjer, M., Lövehagen, N., & Wangel, J. (2014). Smart sustainable cities: Exploring ICT solutionsfor reduced energy use in cities. *Environmental Modelling& Software, 56*, 52–62.
67. Shahrokni, H., Årman, L., Lazarevic, D., Nilsson, A., & Brandt, N. (2015). Implementing smart urban metabolism in the Stockholm Royal Seaport: Smart city SRS. *Journal of Industrial Ecology, 19*(5), 917–929.
68. Bifulco, F., Tregua, M., Amitrano, C. C., & D'Auria, A. (2016). ICT and sustainability in smart cities management. *International Journal of Public Sector Management, 29*(2), 132–147.

69. Keirstead, J., & Leach, M. (2007). Bridging the gaps between theory and practice: A service niche approach to urban sustainability indicators. *Sustainable Development*. http://www3.interscience.wiley.com/journal/116836988/abstract.
70. Curwell, S., & Cooper, I. (1998). The implications of urban sustainability. *Building Research and Information, 26*(1), 17–28.
71. Madden, P., Weißbrod, I. (2008, April). *Connected ICT and sustainable development.* At Forum for the Future.
72. New Scientist. (2006, February 25). *Watering crops in the wireless age*. See also http://nicta.com.au/.f.
73. Kyriazis, D., Varvarigou, T., Rossi, A., White, D., & Cooper, J. (2013). Sustainable smart city IoT applications: Heat and electricity management & Eco-conscious cruise control for public transportation. In *2013 IEEE 14th International Symposium and Workshops on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, https://doi.org/10.1109/WoWMoM.2013.6583500
74. Badii, C., Bellini, P., Cenni, D., Difino, A., Nesi, P., & Paolucci, M. (2017). Analysis and assessment of a knowledge based smart city architecture providing service APIs. *Future Generation Computer Systems, 75*, 14–29.
75. Wenge, R., Zhang, X., Dave, C., Chao, L., & Hao, S. (2014, March). Smart city architecture: A technology guide for implementation and design challenges. *China Communications, 11*(3).
76. Al-Hader, M., Rodzi, A., Sharif, A. R., & Ahmad, N. (2009). Smart city components architecture. *International Conference on Computational Intelligence, Modelling and Simulation, 7–9 Sept. 2009, Brno, Czech Republic, Czech Republic*.
77. Anthopoulos, L., & Fitsilis, P. (2010). From digital to ubiquitous cities: Defining a common architecture for urban development, *6th International Conference on Intelligent Environments. June 19–21. Kuala Lumpur, Malaysia. 2010* (pp. 301–306).
78. Krylovskiy, A., Jahn, M., & Patti, E. (2015, August). Designing a smart city internet of things platform with microservice architecture. In *2015 3rd International Conference on Future Internet of Things and Cloud (FiCloud)* (pp. 25–30). IEEE.
79. Liu, X., Wang, X., Wright, G., Cheng, J. C., Li, X., & Liu, R. (2017). A state-of-the-art review on the integration of building information modeling (BIM) and geographic information system (GIS). *ISPRS International Journal of Geo-Information, 6*(2), 53.
80. Tan, Y., Song, Y., Liu, X., Wang, X., & Cheng, J. C. P. (2017). A BIM-based framework for lift planning in topsides disassembly of offshore oil and gas platforms. *Automation in Construction, 79*, 19–30.
81. Soto, J. Á. C., Werner-Kytölä, O., Jahn, M., Pullmann, J., Bonino, D., Pastrone, C., et al. (2016, January). Towards a federation of smart city services. In *Proceeding of International Conference on Recent Advances in Computer Systems*.
82. Lohan, E. S., Kauppinen, T., & Debnath, S. B. C. (2016, November). A survey of people movement analytics studies in the context of smart cities. In *2016 19th Conference of Open Innovations Association (FRUCT)* (pp. 151–158). IEEE.
83. Volk, R., Stengel, J., & Schultmann, F. (2014). Building information modeling (BIM) for existing buildings—Literature review and future needs. *Automation in Construction, 38*, 109–127.
84. Zdraveski, V., Mishev, K., Trajanov, D., & Kocarev, L. (2017, April–June). ISO-standardized smart city platform architecture and dashboard. *IEEE Pervasive Computing, 16*(2), 35–43.
85. Zhang, K., Ni J., Yang K., Liang X., Ren J., & Shen X. S. (2017, January). Security and privacy in smart city applications: Challenges and solutions. *IEEE Communications Magazine*.
86. Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of things for smart cities. *IEEE Internet of Things Journal, 1*(1), 22–32.
87. Karnouskos, S., & De Holanda, T. N. (2009). Simulation of a smart grid city with software agents. *Third UKSim European Symposium on Computer Modeling and Simulation, 2009. EMS'09*. IEEE, 2009.

88. Morvaj, B., L. Lugaric, & S. Krajcar. Demonstrating smart buildings and smart grid features in a smart energy city. (2011). *Proceedings of the 2011 3rd International Youth Conference on Energetics (IYCE)*. IEEE, 2011.
89. Amini, M. H., Frye, J., Ilić, M. D., & Karabasoglu, O. (2015). Smart residential energy scheduling utilizing two stage mixed integer linear programming. In *North American Power Symposium (NAPS), 2015* (pp. 1–6). IEEE.
90. Siano, P. (2014). Demand response and smart grids—A survey. *Renewable and Sustainable Energy Reviews, 30*, 461–478.
91. Mohsenian-Rad, A.-H., Wong, V. W. S., Jatskevich, J., Schober, R., & Leon-Garcia, A. (2010). Autonomous demand-side management based on game-theoretic energy consumption scheduling for the future smart grid. *IEEE Transactions on Smart Grid, 1*(3), 320–331.
92. Mohammadi, A., Dehghani, M. J., & Ghazizadeh, E. (2018). Game theoretic spectrum allocation in femtocell networks for smart electric distribution grids. *Energies, 11*(7), 1–18.
93. Nguyen, H. K., Song, J. B., & Han, Z. (2012). Demand side management to reduce peak-to-average ratio using game theory in smart grid. In *Computer Communications Workshops (INFOCOM WKSHPS), 2012 IEEE Conference on*. IEEE.
94. Zhang, K., Lu, R., Liang, X., Qiao, J., & Shen, X. S. (2013). PARK: A privacy-preserving aggregation scheme with adaptive key management for smart grid. In *International Conference on Communications in China (ICCC)* (pp. 236–241).
95. Li, X., Lu, R., Liang, X., Shen, X., Chen, J., & Lin, X. (2011, November). Smart community: An internet of things application. *IEEE Communications Magazine, 49*(11), 68–75.
96. Zhang, K., Yang, K., Liang, X., Su, Z., Shen, X., & Luo, H. H. (2015, August). Security and privacy for mobile healthcare networks—From quality of protection perspective. *IEEE Wireless Communications, 22*(4), 104–112.
97. Neirotti, P., Marco, A. D., Cagliano, A. C., Mangano, G., & Scorrano, F. (2014). Current trends in smart city initiatives: Some stylised facts. *Cities, 38*, 25–36.
98. Ni, J., Lin, X., Zhang, K., & Shen, X. (2016). Privacy-preserving real-time navigation system using vehicular crowd-sourcing. In *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)* (pp. 1–5).
99. Clough, B. A., & Casey, L. M. (2015). The smart therapist: A look to the future of smartphones and mHealth technologies in psychotherapy. *Professional Psychology: Research and Practice, 46*(3), 147.
100. Amini, M. H., & Islam, A. (2014). Allocation of electric vehicles' parking lots in distribution network. *Innovative Smart Grid Technologies Conference (ISGT), 2014 IEEE PES*. IEEE, 2014.
101. Amini, M. H., Karabasoglu, O., Ilić, M. D., Boroojeni, K. G., & Iyengar, S. S. (2015). ARIMA-based demand forecasting method considering probabilistic model of electric vehicles' parking lots. In *Power & Energy Society General Meeting, 2015, IEEE* (pp. 1–5). IEEE.
102. Amini, M. H., Kargarian, A., & Karabasoglu, O. (2016). ARIMA-based decoupled time series forecasting of electric vehicle charging demand for stochastic power system operation. *Electric Power Systems Research, 140*, 378–390.
103. Amini, M. H., Boroojeni, K. G., Wang, C. J., Nejadpak, A., Iyengar, S. S., & Karabasoglu, O. (2016). Effect of electric vehicle parking lots' charging demand as dispatchable loads on power systems loss. In *2016 IEEE International Conference on Electro Information Technology (EIT)* (pp. 0499–0503). IEEE.
104. Amini, M. H., & Karabasoglu, O. (2017). *Optimal operation of interdependent power systems and electrified transportation networks*. arXiv preprint arXiv:1701.03487.
105. Amini, M. H., Nabi, B., Moghaddam, M. P., & Mortazavi, S. A. (2012). Evaluating the effect of demand response programs and fuel cost on PHEV owners behavior, a mathematical approach. In *2012 2nd Iranian Conference on Smart Grids (ICSG)*. IEEE.
106. Viswanath, A., & Farid, A. M. (2014). A hybrid dynamic system model for the assessment of transportation electrification. *American Control Conference (ACC)*. IEEE, 2014.

107. Mozafar, M. R., Moradi, M. H., & Amini, M. H. *A simultaneous approach for optimal allocation of renewable energy sources and electric vehicle charging stations in smart grids based on improved GA-PSO algorithm*.
108. Amini, M. H., Moghaddam, M. P., & Karabasoglu, O. (2017). Simultaneous allocation of electric vehicles' parking lots and distributed renewable resources in smart power distribution networks. *Sustainable Cities and Society, 28*, 332–342.
109. Mistani, P., Guittet, A., Bochkov, D., Schneider, J., Margetis, D., Ratsch, C., et al. (2018). The island dynamics model on parallel quadtree grids. *Journal of Computational Physics, 361*, 150–166.
110. Kamienski, C. A., Borelli, F. F., Biondi, G. O., Pinheiro, I., Zyrianoff, I. D., & Jentsch, M. (2017). Context design and tracking for IoT-based energy management in smart cities. *IEEE Internet of Things Journal, 5*(2), 687–695.
111. Morello, R., Mukhopadhyay, S. C., Liu, Z., Slomovitz, D., & Samantaray, S. R. (2017). Advances on sensing technologies for smart cities and power grids: A review. *IEEE Sensors Journal, 17*(23), 7596–7610.
112. Cerna, F. V., Pourakbari-Kasmaei, M., Romero, R. A., & Rider, M. J. (2017). Optimal delivery scheduling and charging of EVs in the navigation of a city map. *IEEE Transactions on Smart Grid, 9*(5), 4815–4827.
113. Amini, M. H., McNamara, P., Weng, P., Karabasoglu, O., & Xu, Y. (2017). Hierarchical electric vehicle charging aggregator strategy using Dantzig-Wolfe decomposition. *IEEE Design & Test Magazine*. https://doi.org/10.1109/MDAT.2017.2759505.
114. Mazza, D., Pagès-Bernaus, A., Tarchi, D., Juan, A. A., & Corazza, G. E. (2018). Supporting mobile cloud computing in smart cities via randomized algorithms. *IEEE Systems Journal, 12*(2), 1598–1609.
115. Ota, K., Kumrai, T., Dong, M., Kishigami, J., & Guo, M. (2017) Smart infrastructure design for Smart Cities, IT Professional (Early Access), https://doi.org/10.1109/MITP.2017.265110715.
116. Gholami, A., Shekari, T., Amirioun, M. H., Aminifar, F., Amini, M. H., & Sargozalei, A. (2018). Toward a consensus on the definition and taxonomy of power system resilience. *IEEE Access, 6*, 32035–32053.
117. Boroojeni, K. G., Amini, M. H., & Iyengar, S. S. (2017). Overview of the security and privacy issues in smart grids. In *Smart grids: Security and privacy issues* (pp. 1–16). Cham: Springer International Publishing.
118. Martinez-Balleste, A., Perez-Martinez, P., & Solanas, A. (2013, June). The pursuit of citizens' privacy: A privacy-aware smart city is possible. *IEEE Communications Magazine, 51*(6), 136–141.
119. Elmaghraby, A. S., & Losavio, M. (2014). Cyber security challenges in smart cities: Safety, security and privacy. *Journal of Advanced Research, 5*(4), 491–497.
120. Weber, R. H. (2010). Internet of things—New security and privacy challenges. *Computer Law and Security Review, 26*(1), 23–30.
121. Naphade, M., Banavar, G., Harrison, C., Paraszczak, J., & Morris, R. (2011). Smarter cities and their innovation challenges. *IEEE Computer, 44*(6), 32–39.
122. Roman, R., Zhou, J., & Lopez, J. (2013). On the features and challenges of security and privacy in distributed internet of things. *Computer Networks, 57*(10), 2266–2279.
123. Akhunzada, A., Ahmed, E., Gani, A., Khan, M. K., Imran, M., & Guizani, S. (2015, April). Securing software defined networks: Taxonomy, requirements, and open issues. *IEEE Communications Magazine, 53*(4), 36–44.

Chapter 4
Towards a Tensor Network Representation of Complex Systems

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"It is not the strongest of the species that survives, nor the most intelligent, but the one most responsive to change."
Charles Darwin (1809)

Introduction

Overview

Complex networks are composed of nodes (entities) and edges (connections) with any arbitrary topology. There may also exist multiple types of interactions among these nodes as well as each node may admit different states in each of its interactions with its neighbors. Understanding complex networks dwells on understanding their structure and function. However, traditional representations of complex networks model nodes as single-state entities that are connected to each other differently and treat their dynamics separately with some differential equations. Alternatively, a unified framework might be accessible using the tensor network representation that is already utilized in physics communities. In a sequel of chapters we introduce tensor network representation and renormalization of complex networks as an alternative framework to explore the universal behaviors of complex systems. We hope that tensor networks can particularly pave the way

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for better understanding of the sustainable interdependent networks [2] through proposing efficient computational strategies and discovering insightful features of the network behaviors.

Network Structure During the past two decades, structural studies of real complex networks revealed several universal characteristics: (1) *scale-free* degree distribution, (2) power-law decay of interaction probability over distance, (3) modularity or *community structure*, (4) embedded dimensionality, (5) small world feature, (6) fractal structure, and more. Here we briefly review a few of these properties.

Scale-free networks are characterized by a power-law for the degree distribution of the nodes. In such networks, the probability of having k edges for each node drops according to $P(k) \sim k^{-\gamma}$. The vast spectrum of complex natural and artificial phenomena can be modeled as complex *scale-free* networks such as genetic networks, nervous systems, World Wide Web, social networks, and many more [1, 6].

Also, it has been shown that most real complex networks not only exhibit power-law distribution for their connectivities but also the length distribution of the edges follows some power-law form, i.e. $P \sim r^{-\delta}$, where $\delta = 0$ resembles long range interactions while $\delta \to \infty$ represents short range interactions [17]. For instance, in a mobile phone network the communication probability of two customers decays with a gravity-like model of $P \sim r^{-2}$ and the degree distribution exhibits another power-law with $P \sim k^{-5}$ [32], or in an airline network the probability of direct flights drops with $P \sim r^{-3}$ [9].

Modularity refers to the clustering of smaller communities in a network that are relatively loosely connected to the rest of the network. Subsequently, these communities could join to form metacommunities in a *hierarchical structure* [30].

Furthermore, Daqing et al. [17] have shown how the degree distribution and edge lengths can effectively determine a dimension for the spatial embedding of the complex network. Such a spatial embedding generates a d_f-dimensional regular lattice representation for arbitrary complex networks.

The ultimate goal of network science is to understand the behavior of network systems in terms of processes that are performed by these networks. For example, in the case of power grids we are interested to know how the grid structure affects power distribution and the resilience of the network to failures or how an avalanche of failures occur in the network, or in the case of WWW one is interested to know how the architecture of the network affects internet surfing. Hence, despite the aforementioned tomography of complex networks, attempts have also been made to analyze network stability against damage to its underlying structure, i.e. through failure of nodes or removal of connections such as failure in transmission lines in power grids or failure in routers in the case of WWW. To this end, *percolation theory* from statistical physics has been extensively used to understand the resilience of a network during a percolation process via finding the critical fraction of nodes where the network fragments into disjoint clusters [12, 15]. Consequently, percolation provides a means to design robust network topologies. We note that percolation is the simplest example where continuous phase transitions occur in statistical physics because interactions in the network are ignored in this process and only the occupation fraction plays a role [23].

Network Functionality Despite quantifying the *structure* of complex networks, it is also important to understand, model, and predict their *functionality* as an individual entity. Even though many universal properties of network structures have been found, few attempts have been made towards a unifying framework to analyze network dynamics, e.g. look at [7] for a perturbative approach. Perhaps this is because an understanding of network functionality logically proceeds understanding the structure of networks. So far, experimental studies have mostly focused on measurements of the correlation matrix G_{ij} between nodes i and j. G_{ij} captures the linear response of the dynamical value at node j, for example some reactant concentration in the case of biochemical networks, to a perturbation at the value of node i [37]. This is formally defined as:

$$G_{ij} = \frac{d(\log x_i)}{d(\log x_j)}, \tag{4.1}$$

Interestingly, many measurements of the distribution of this pair-wise correlation function discovered another power-law form [7]:

$$P(G) \sim G^{-\nu}. \tag{4.2}$$

In these two chapters, motivated by these scaling laws we will investigate the asymptotic behavior of complex systems at large scales, i.e. or at thermodynamic limit as in the terminology of statistical physics, and review some of the literature concerning the universality of behaviors in complex systems. In the next chapter, we will introduce the powerful machinery of *renormalization group (RG)* theory primarily developed to investigate phase transitions in quantum many-body systems and try to explain emergence of power-law scaling functions. We aim to justify the exciting opportunities that applications of real space renormalization group methods [25] provide for the study of asymptotic behaviors of complex networks. RG methods can be used to find the universal behavioral classes for complex systems that is essentially dictated by network topology, its dimensionality, and the underlying symmetries in the interactions.

Other Resources on Complex Networks

Here we do not aim to review the huge literature on complex networks and rather only focus on modern ideas from statistical physics and their possible application to studies of complex systems. For standard reviews of the field from the perspective of statistical physics, we refer to Albert and Barabasi [1] or Dorogovtsev and Mendes [24]. These references mostly concentrate on models of growing graphs, however we find the review by Newman [44] of particular importance as it focuses on both structure and dynamics of complex networks.

Collective Behavior of Self-organized Systems

In this section we present a perspective to understand the different behaviors observed in complex systems. We will focus on two of the most prominent ones: scale-free and hierarchical or modular behaviors. The key concept in discerning among these states is the behavior of the "correlations" among individuals. Yet another important concept is that of "order." First we try to explain how correlations discern among many asymptotic behaviors and later we will discern between the notion of order and correlation.

Collective Behaviors and State of Maximum Responsiveness

Scale-free correlations have been observed in a myriad of complex systems: in large flocks of starlings [13], flocks of birds [8], road networks [42], neural networks [55], etc. Particularly, Mora and Bialek [43] have shown that natural systems operate near critical points in their parameter space. The hallmark of systems at criticality is the presence of scale-free correlations. Remarkably, it has been shown that scale-free behaviors provide the maximal responsiveness of individuals in a system to their environment [13].

As pointed by [13], self-organized natural systems need to respond collectively to, for instance, perception of a threat by any member of the group, for example a flock of starlings has to dodge a falcon's attack in synchrony. In this view, it is the requirement of maximal sensitivity and responsiveness in a natural system to its environment that induces scale-free correlations in the system via a self-organization process. In such systems information is accessible by all elements such that the functionality of each element is affected by all others regardless of the physical distances among them. Furthermore, in these systems control occurs by the collective interactions among the elements. This is eventually observed as an infinite correlation length or the scale-free property of complex systems.

However, the correlation length of systems observed in nature is not always infinite, or bigger than the group size. For example, in the case of the collective swimming of herds of bacteria observed at high cell concentrations, [14] have shown the correlation length is smaller than the size of the swarm of bacteria. This effectively separates different communities of bacteria which are only weakly interacting with each other. In the case of smaller correlation lengths, the system can be effectively divided into sub-systems that each behaves independently to the perturbations in their environment. This feature also resembles the *hierarchical* nature of some complex networks. In hierarchical systems, control is centralized and information/organization flows from leader to lower levels of the hierarchy, e.g. examples are mostly observed in social settings and organizations. In hierarchical organizations, the system will respond to environment only if the leader perceives the perturbation.

Counterintuitively, maximal order does not necessarily follow from the maximal correlation among individuals in the system. As argued in reference [13], for example in the case of ferromagnetism the disorder parameter (i.e., temperature) must be set to its Curie value in order to observe maximal correlations among spins, i.e. note that this is a nonzero value for disorder/noise in the system. It is important to emphasize that the state of maximum correlation does not correspond to the absence of noise in the system, nevertheless some amount of the disorder parameter is necessary to maintain a scale-free response.

In statistical physics sense, it is in the vicinity of the critical fixed points of a system that scale-free behaviors emerge via symmetry breakings. Hence, biological systems living at criticality exhibit the highest evolutionary chance of survival. Particularly, Longo et al. [34] have proposed that "biology is characterized by a relentless breaking of symmetries" and they bridge between physics and biology through the notion of *extended criticality*. Extended criticality might be the distinguishing factor between inert and the living state of matter [33]. We highly recommend the interesting paper by Longo et al. [34] for a discussion of how these concepts from physics can be generalized to improve our understanding of biological systems.

Effective Perception Range Through Feedback

As discussed above, scale-free systems exhibit correlation length-scales comparable to the size of the system. However, in the formation flight of starlings every individual bird is only monitoring a few of its nearest neighbors in a topological sense [8] via some sensory modalities such as vision, sound, pressure, and odor detection. Despite this limited range of actual sensory devices, the group of birds manage to act in harmony in a way that a localized change in direction is felt throughout the entire group. It is through *positive feedback* that information mediates in the group and the collective mindfulness emerges [16]; see Fig. 4.1. The effective perception in a complex system *emerges* out of the collective interactions of its constituents. In the most basic case where elements of the system act absolutely *independently* to contribute to a net output for the system, the output is equal to the sum of its parts plus or minus a standard deviation proportional to the square root of the number of elements. This is the celebrated "central limit theorem" which hypothesizes a normal distribution for such collective phenomena:

$$\text{Normal pdf}: P(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\Big(-\frac{(x-\mu)^2}{2\sigma^2}\Big),$$

$$\text{expectation value}: \mu \sim N,$$

$$\text{uncertainty}: \sigma \sim \sqrt{N}.$$

Fig. 4.1 Collective mind of starlings through information feedback. This image is adopted from [16]

It is in this spirit that the normal distribution serves as a null hypothesis for measuring the degree of *independence* in a system and the amount of deviation from it determines the degree of *interdependence*. This interdependence is usually in the form of feedback that leads to self-organization [52, 54] (Fig. 4.1).

Feedback comes in different forms [10]: (1) "positive feedback" or "amplification" through recruitment or reinforcement of individual events, e.g. trail laying and trail following mechanisms in ant colonies for food recruitment, (2) "negative feedback" which works against positive feedback to stabilize the collective pattern, e.g. food exhaustion or some sort of competition.

An interesting example of feedback arises in epidemic outbreaks (Fig. 4.2). In this case, the interplay occurs between contagious processes and social networks. Social networks can increase awareness with respect to the disease such that preventive actions are more likely to be taken by susceptible population, this subsequently reduces infection rates and helps to stop the epidemics. Awareness models consider oblivion over time and updating of awareness via infection of more population as more sources of news chains. This produces a feedback loop in which spread of a disease raises awareness, which subsequently reduces infection rates, however less infected people lead to insensibility to the infection which might cause

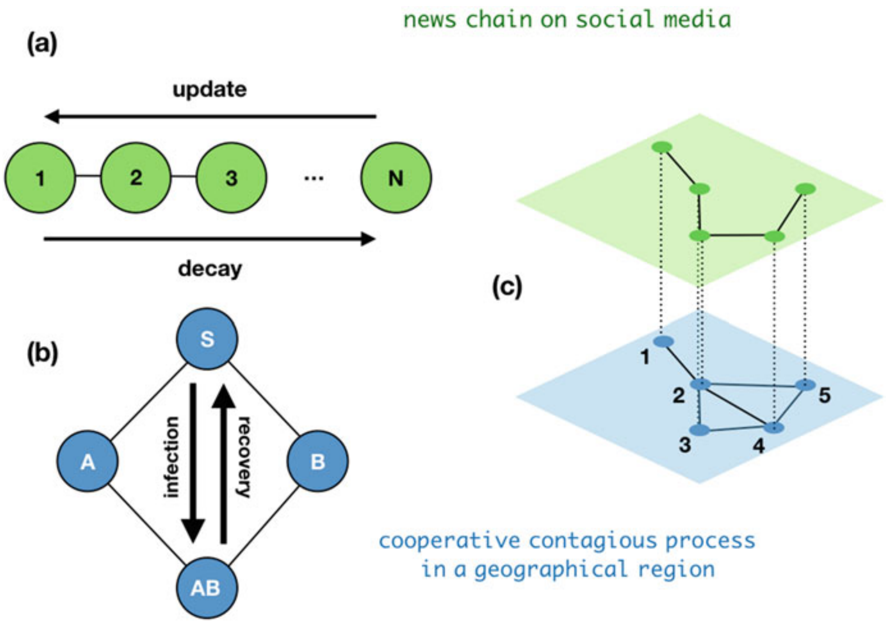

Fig. 4.2 Syndemics with news propagation in a two-layer interdependent network. (**a**) shows different levels of awareness regarding the disease, (**b**) is the contagious process where S is the susceptible population, A and B are two diseases populations, and AB is the population infected by both A and B contagions. The interdependence between the two layers (**c**) occurs by changing infection and recovery rates, as well as providing sources for extra news chains when infection appears. Note that in (**c**) the same nodes exist in both social and geographical networks

the next phase of an outbreak. Due to this competition, there will be phase transitions between different dominant phases for the epidemic [29, 36, 38].

Of course there are many factors that are responsible for the collective patterns observed in complex systems, a few other factors are: integrity and variability, response thresholds, leadership, redundancy, synchronization, inhibition, selfishness, and maybe more. Look at the classic review of Sumpter [54] for an extensive description of responsible factors in self-organization.

On the other hand in interdependent networks, networks of networks are connected by *dependency* links. The distinguishing aspect of dependency links is that they only represent mutual dependence between nodes of different networks, i.e. if one end fails the other will fail too, in contrast to the usual connectivity of nodes in a network which implies a *flow* between the connected nodes. For instance, a power station in an electric power grid depends on the energy network by receiving fuel for maintaining its generators as well as providing the required electricity to maintain the control system and storage for the energy network. Even though such dependencies do not explicitly change the flows in the network, but they *interact* with the flows going through each node via a feedback loop [3, 39, 41].

An Alternative Framework

In current network representations, there are two inherent deficiencies: (1) nodes are single-state entities, and consequently (2) an edge represents a *binary* interaction determined by the singular state of the connected nodes. The ignorance of current network models to respect multiple states for each node, e.g. characterized by different levels of functionality, and ignoring different interactions between them prohibit realistic analysis of complex networks in many different ways.

For example in a power grid, malfunction of a power station due to a deficiency in a dependent ingredient may not lead to its total shutdown but rather to a reduction in its efficiency. However, the lowered performance of this node may propagate throughout the network and cause a cascade or avalanche of failures at more sensitive nodes by overloading them beyond their tolerance. These nodes might not be spatially correlated, i.e. "action at a distance," or even be in the same network. Such an avalanche happened in the USA in August 1996 from a power outage in El Paso, Texas, that spread to over six states in the western USA. This phenomenon is also observed in the case of the protein-protein-binding network in yeast *Saccharomyces cerevisiae* where a perturbation in the concentration of one node propagates to considerably distant nodes up to four steps away [37].

Note *Multiplex networks are a sub-class of interdependent networks that same nodes are replicated in different layers with different connectivities. Here layers represent different interaction types and depend on each other. Attempts to represent multiplex networks have utilized a tensorial framework (see references [21, 22, 59]). However, nodes on these networks are single state entities, while here we propose an alternative framework where each node is itself a multi-state entity. This may facilitate understanding dynamics of interdependent networks.*

For a comprehensive study of correlations in multiplex networks, look at [45] and for an example of studying infectious processes on multiplex networks using this framework, see [20].

Tensor Network Representation of Complex Systems

To circumvent these deficiencies an alternative proposal might be to represent complex networks with *tensor networks* in which each node is modeled as a *tensor operator* that is connected to other tensors. In this approach, each link may carry χ number of discrete values and hence represents a state-vector in a χ-dimensional vector space. The nodes act as operators among their adjacent vector spaces. In quantum mechanics terminology, tensor networks constitute the building blocks of the *wavefunction* describing the overall state of the system [46].

We mention that the idea to use a field theoretic renormalization group theory (FTRG) for complex graphs has been proposed in the interesting work of [4]. In their approach, "The idea is to expand order parameter fluctuations in eigenvectors of the graph Laplacian, write down the equivalent of a Ginzburg-Landau Hamiltonian, and then perform partial summations over the partition function, to eliminate the high-eigenvalue components" [4]. However, we are focusing on the possibility of using tensor network renormalization group methods as a *numerical* coarse-graining strategy to find fixed points of complex systems.

In the following subsections we will lay out the conceptual foundation to justify the tensor network representation of complex systems.

Von-Neumann Entropy and Entanglement in Complex Networks

Density Matrix In quantum many-body systems the *density matrix* ρ encapsulates all the accessible information about the system. Density matrix is a Hermitian and semi-definite matrix with a unitary trace. This matrix admits a spectral decomposition:

$$\rho = \sum_{i=1}^{N} \lambda_i \left|\phi_i\right\rangle \left\langle\phi_i\right| ,$$

where $\{\phi_i\}$ is an orthonormal basis and λ_i's are non-negative eigenvalues that have the property $\sum_{i=1}^{N} \lambda_i = 1$. Given this matrix, one can evaluate the Von Neumann entropy that essentially extends the Shannon entropy to quantum systems:

$$S(\rho) = -\mathrm{Tr}\big(\rho \log_2 \rho\big) = -\sum_{\mathrm{i}=1}^{\mathrm{N}} \lambda_{\mathrm{i}} \log_2 \lambda_{\mathrm{i}}.$$

whose maximum value is bounded by 0 and $\log_2 N$ [60]. A candidate for density matrix of a complex network which satisfies the mathematical constraints was proposed in the seminal work of [11]. They have shown that for an undirected complex network, the combinatorial graph Laplacian $L = D - A$ where A is the adjacency matrix and D its degree distribution can be used to construct a density matrix as follows:

$$\rho = \frac{L}{\mathrm{Tr}\big(L\big)}.$$

Obviously this definition is symmetric and positive semi-definite and has unitary trace. Notably this definition has been used by [22] for monoplex and multiplex networks. However, we note that this definition for density matrix does not satisfy the subadditivity condition of the Von Neumann entropy in some special cases, as a result the very interesting reference [19] has proposed another density matrix based on the diffusion operator $e^{-\tau L}$ at time τ:

$$\rho = \frac{\mathrm{e}^{-\tau \mathrm{L}}}{\mathrm{Tre}^{-\tau \mathrm{L}}}.$$

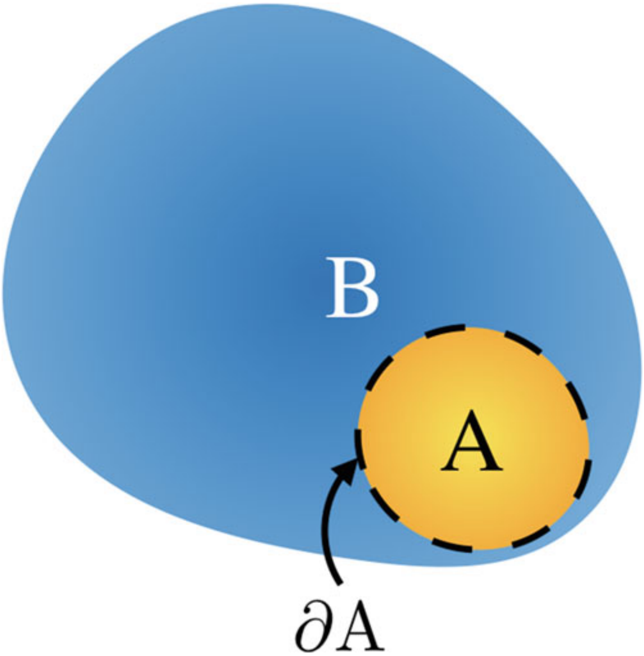

Fig. 4.3 The composite system AB can be partitioned in two parts, the amount of entanglement is proportional to the area of the boundary ∂A

This new density matrix corresponds to the so-called *spectral entropy* which satisfies the subadditivity condition at all situations.

Entanglement In a bipartite quantum system, Fig. 4.3, the amount of entanglement of a subregion A with the rest of the system is measured by the entanglement entropy:

$$S(A) = -\mathrm{Tr}\big(\rho_{\mathrm{A}} \log_2 \rho_{\mathrm{A}}\big),$$

where ρ_A is the reduced density matrix by summing over the rest of the system denoted by B in the ground state $|\psi_{GS}\rangle$:

$$\rho_{\mathrm{A}} = \mathrm{Tr}_{\mathrm{B}}\big(|\psi_{\mathrm{GS}}\rangle \langle\psi_{\mathrm{GS}}|\rangle\big).$$

where $\mathrm{Tr}_{\mathrm{B}}\big(|\mathrm{A}\rangle \langle\mathrm{A}|\rangle |\mathrm{B}\rangle \langle\mathrm{B}|\rangle\big) = |\mathrm{A}\rangle \langle\mathrm{A}| \,\mathrm{Tr}\big(|\mathrm{B}\rangle \langle\mathrm{B}| \big)$. The Von Neumann entropy is defined:

$$S = -\mathrm{Tr}\big(\rho \log_2 \rho\big).$$

and is interpreted as the entanglement of the statistical ensemble of pure states where each pure state can be seen as an edge in the graph [18]. The bigger this quantity, the more entanglement exists in the network. A Von Neumann entropy of zero corresponds to a fully pure state.

Area Law The most remarkable aspect of entanglement entropy is due to the *locality* of interactions in the hamiltonian of the system which impose the *area law* constraint on the accessible ground states to the realistic systems [53]. Specifically, the entanglement entropy of a large enough region in a D-dimensional lattice scales with the size of its boundary and not its enclosed volume:

$$S(A) \sim |\partial A| \sim L^{\mathrm{D}-1}.$$

In this subsection we have seen how one can measure the amount of entanglement entropy in a given complex system using an information theoretic approach to complex networks. For our purposes we only mention that the structure of entanglement in the system is a key aspect in proceeding with the tensor network representations and here we have only touched upon the conceptual foundations that one needs in this venue.

Representational Power of Tensor Network States

A tensor network state is a collection of tensors that are interconnected according to a network topology which in turn captures the entanglement in the system. Depending on the dimensionality of the underlying lattice one has many types of tensor network ansatz: in 1D lattice systems there are matrix product states (MPS) [27, 47, 48], the multi-scale entanglement renormalization ansatz (MERA) [57, 58] as well as tree tensor networks (TTN) [50]; one can also generalize these states to higher dimensions $D > 1$. For example, the projected entangled pair states (PEPS) [56] is the generalization of MPS to higher dimensions. It has been shown that MPS architectures can precisely reproduce the ground state of the 1D many-body systems for high enough values of χ. Same is true for MERA which is also capable to reproduce the large scale ground state properties of scale-invariant systems, e.g. for example the two-point correlators are easily reproduced. Notably MERA is able to capture both infinite and finite correlation length-scales, ξ.

Evenbly and Vidal [26] have argued that the physical and holographic geometries of tensor network states determine the asymptotic decay of correlations in homogeneous MPS and MERA for $D = 1$ systems, respectively, i.e. asymptotic behaviors are the power-law or the exponential modes as introduced earlier. The physical geometry is only determined by the patterns of interactions in the system and is essentially identical to the underlying lattice. In a familiar sense, MPS and PEPS can also be considered as the one- and two-dimensional discretizations of the continuous space. On the other hand, the holographic geometry is determined by the pattern of entanglements in the ground state of the system.

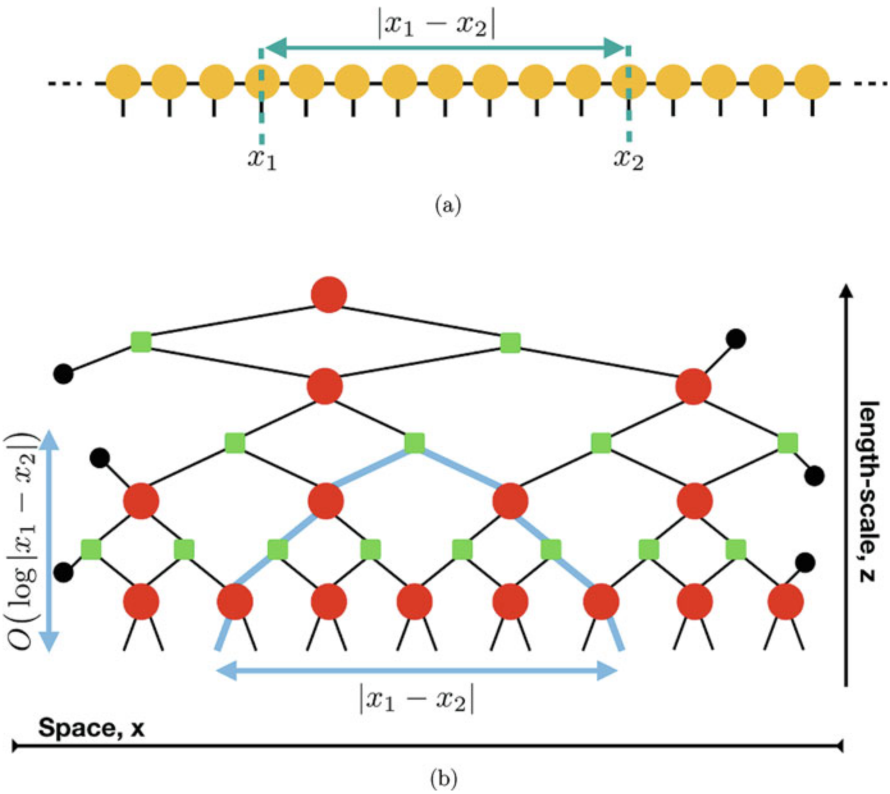

Fig. 4.4 (**a**) A $1D$ MPS composed of homogeneous tensors. (**b**) The homogeneous and scale invariant MERA for a 1D lattice. The vertical direction exhibits the entanglements/correlations as they appear in different length-scales of the system. The horizontal direction corresponds the spatial configuration of the lattice. There are two types of tensors in MERA: disentanglers in green and isometries in red. In both networks the geodesics are highlighted as the shortest path between any two positions in the lattice

The holographic geometry is usually captured by adding an extra dimension to the physical lattice which is incorporated to the wiring of a MERA architecture. Inspired by the holographic principle [35] the logarithm of length-scale $z = \log_2 b$ is usually adopted as the extra dimension. See Fig. 4.4 for an illustration of MERA for a one-dimensional lattice model.

As in Fig. 4.4 the correlation lengths for the MPS and the scale-invariant MERA can be computed by observing that:

$$\text{MPS} : D_{phys}(x_1, x_2) = |x_1 - x_2| \rightarrow C_2^{\text{MPS}}(x_1, x_2) \approx e^{-D_{phys}/\xi} \approx e^{-|x_1 - x_2|/\xi},$$

$$\text{MERA} : D_{hol}(x_1, x_2) = \log_2 \left(|x_1 - x_2|\right) \rightarrow C_2^{\text{MERA}}(x_1, x_2) \approx e^{-\alpha D_{hol}} \approx |x_1 - x_2|^{-\gamma}.$$

These notions emphasize that the representational power of the correlations in these families of network states is hidden in the geometry of these networks and does not depend on the choice of variational parameters.

Modeling Interactions

The first challenge in this approach is to construct a suitable hamiltonian for the interactions in the system. Here we will review the generic strategy for complex systems with only pair-wise correlations as proposed by [49]. Practically, the strategy is to capture the low-order global statistics of the network up to the one-point correlators $<S_i>$ and two-point correlators $C_{ij} =<S_i S_j>$ in the hamiltonian [5]. The resulting Hamiltonian reads:

$$H = \sum_i h_i S_i + \frac{1}{2}\sum_{i \neq j} J_{ij} S_i S_j,$$

For example, this model has been shown to be an exact mapping in the case of spikes in a neural population in the vertebrate retina [49]. The maximum entropy principle provides the least structured model consistent with observations on the system. Consequently, the minimalistic distribution function consistent with a known average energy $< E >$ is the Boltzmann distribution:

$$P \sim \exp\Big\{\Big(- E/K_B T\Big)\Big\}$$

where k_B is the Boltzmann constant and T is temperature. The generalized version of a Boltzmann distribution when averaged values of multiple observables f_i are available reads:

$$P \sim \exp\Big\{\Big(\sum_i g_i f_i\Big)\Big\}$$

where g_i are the Lagrange multipliers for each constraint/observation on the system. Following Azhar et al., this reduces to an inverse statistical mechanics problem to find the probability distribution function:

$$P(S_i) = \frac{1}{Z(\{h_i, J_{ij}\})} \exp\Big\{\Big(\sum_i h_i S_i + \frac{1}{2}\sum_{i \neq j} J_{ij} S_i S_j\Big)\Big\},$$

where $\{h_i, J_{ij}\}$ are the Lagrange multipliers fixed by constraining the first two order correlators. Here, $Z(\{h_i, J_{ij}\})$ is the *partition function* defined as the ensemble sum of all configurations:

$$Z(\{h_i, J_{ij}\}) = \sum_{\{S_i\}} \exp\Big\{\Big(\sum_i h_i S_i + \frac{1}{2}\sum_{i \neq j} J_{ij} S_i S_j\Big)\Big\}.$$

For completeness, we also mention that in a game theory problem as in many real networks where a *normal form* formulation of the *game* is available, the interaction hamiltonian is the *payoff function* by which nodes interact and the renormalization should be performed on the *space of strategies*. RG will find fixed points of the best response dynamics which are also the Nash equilibria of the game [28, 51].

We note that game theoretic approaches have recently been used to understand the interdependent electric power grids, for example see, for example look at [31, 40].

We end this section by emphasizing that the statistical distribution found above is used to define the thermodynamic quantity of *free energy*, F, as the logarithm of the sum, or trace as a linear operator, of the Boltzmann weights over all possible configurations:

$$Z = e^{-\beta F} = \mathrm{Tr}_{\{S_i\}} e^{-\beta H\{S_i\}},$$

Here Z is the aforementioned partition function. Partition function or equivalently the free energy are the quantities that are explicitly preserved through the renormalization transformation whose significance is that they encapsulate all thermodynamical observables of the system such as the correlation functions, phase transitions and critical exponents, universality classes, ensemble averages, etc.

Conclusion

In the broad field of self-organization, inspired by the similarities in between the natural complex systems researchers have been in pursuit of a unifying theory or an *ultra-calculus* as Sumpter puts it. So far, we have laid the foundation for an alternative representation of complex systems using tensor networks that is inherently capable to model the universal behaviors of complex systems.

In the next chapter we will borrow another tool for understanding phase transitions from statistical physics, namely the *renormalization group (RG)* theory, in order to find the fixed points of complex system dynamics. Hence, RG seems to be a promising ultra-calculus which can detect the universalities among the myriad of complex systems.

References

1. Albert, R., & Barabási, A.-L. (2002). Statistical mechanics of complex networks. *Reviews of Modern Physics, 74*(1), 47.
2. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks: From theory to application* (Vol. 145). Cham: Springer.

3. Amini, M. H., & Karabasoglu, O. (2018). Optimal operation of interdependent power systems and electrified transportation networks. *Energies, 11*(1), 196.
4. Aygün, E., & Erzan, A. (2011). Spectral renormalization group theory on networks. *Journal of Physics: Conference Series, 319*, 012007. IOP Publishing.
5. Azhar, F., & Bialek, W. (2010). *When are correlations strong*? arXiv preprint arXiv:1012.5987.
6. Barabási, A.-L., & Albert, R. (1999). Emergence of scaling in random networks. *Science, 286*(5439), 509–512.
7. Barzel, B., & Barabási, A.-L. (2013). Universality in network dynamics. *Nature Physics, 9*(10), 673.
8. Bialek, W., Cavagna, A., Giardina, I., Mora, T., Silvestri, E., Viale, M., & Walczak, A. M. (2012). Statistical mechanics for natural flocks of birds. *Proceedings of the National Academy of Sciences of the United States of America, 109*(13), 4786–4791.
9. Bianconi, G., Pin, P., & Marsili, M. (2009). Assessing the relevance of node features for network structure. *Proceedings of the National Academy of Sciences of the United States of America, 106*(28), 11433–11438.
10. Bonabeau, E., Theraulaz, G., Deneubourg, J.-L., Aron, S., & Camazine, S. (1997). Self-organization in social insects. *Trends in Ecology & Evolution, 12*(5), 188–193.
11. Braunstein, S. L., Ghosh, S., & Severini, S. (2006). The laplacian of a graph as a density matrix: A basic combinatorial approach to separability of mixed states. *Annals of Combinatorics, 10*(3), 291–317.
12. Callaway, D. S., Newman, M. E., Strogatz, S. H., & Watts, D. J. (2000). Network robustness and fragility: Percolation on random graphs. *Physical Review Letters, 85*(25), 5468.
13. Cavagna, A., Cimarelli, A., Giardina, I., Parisi, G., Santagati, R., Stefanini, F., et al. (2010). Scale-free correlations in starling flocks. *Proceedings of the National Academy of Sciences of the United States of America, 107*(26), 11865–11870.
14. Cisneros, L. H., Kessler, J. O., Ganguly, S., & Goldstein, R. E. (2011). Dynamics of swimming bacteria: Transition to directional order at high concentration. *Physical Review E, 83*(6), 061907.
15. Cohen, R., Erez, K., Ben-Avraham, D., & Havlin, S. (2000). Resilience of the internet to random breakdowns. *Physical Review Letters, 85*(21), 4626.
16. Couzin, I. (2007). Collective minds. *Nature, 445*(7129), 715.
17. Daqing, L., Kosmidis, K., Bunde, A., & Havlin, S. (2011). Dimension of spatially embedded networks. *Nature Physics, 7*(6), 481.
18. de Beaudrap, N., Giovannetti, V., Severini, S., & Wilson, R. (2016). Interpreting the von neumann entropy of graph laplacians, and coentropic graphs. *A Panorama of Mathematics: Pure and Applied, 658*, 227.
19. De Domenico, M., & Biamonte, J. (2016). Spectral entropies as information-theoretic tools for complex network comparison. *Physical Review X, 6*(4), 041062.
20. De Domenico, M., Granell, C., Porter, M. A., & Arenas, A. (2016). The physics of spreading processes in multilayer networks. *Nature Physics, 12*(10), 901.
21. De Domenico, M., Nicosia, V., Arenas, A., & Latora, V. (2015). Structural reducibility of multilayer networks. *Nature Communications, 6*, 6864.
22. De Domenico, M., Solé-Ribalta, A., Cozzo, E., Kivelä, M., Moreno, Y., Porter, M. A., et al. (2013). Mathematical formulation of multilayer networks. *Physical Review X, 3*(4), 041022.
23. Dorogovtsev, S. N., Goltsev, A. V., & Mendes, J. F. (2008). Critical phenomena in complex networks. *Reviews of Modern Physics, 80*(4), 1275.
24. Dorogovtsev, S. N., & Mendes, J. F. (2002). Evolution of networks. *Advances in Physics, 51*(4), 1079–1187 (2002).
25. Efrati, E., Wang, Z., Kolan, A., & Kadanoff, L. P. (2014). Real-space renormalization in statistical mechanics. *Reviews of Modern Physics, 86*(2), 647.
26. Evenbly, G., & Vidal, G. (2011). Tensor network states and geometry. *Journal of Statistical Physics, 145*(4), 891–918.
27. Fannes, M., Nachtergaele, B., & Werner, R. F. (1992). Finitely correlated states on quantum spin chains. *Communications in Mathematical Physics, 144*(3), 443–490.

28. Fáth, G., & Sarvary, M. (2005). A renormalization group theory of cultural evolution. *Physica A: Statistical Mechanics and Its Applications, 348*, 611–629.
29. Funk, S., Gilad, E., Watkins, C., & Jansen, V. A. (2009). The spread of awareness and its impact on epidemic outbreaks. *Proceedings of the National Academy of Sciences of the United States of America, 106*(16), 6872–6877.
30. Girvan, M., & Newman, M. E. J. (2002). Community structure in social and biological networks. *Proceedings of the National Academy of Sciences of the United States of America, 99*(12), 7821–7826.
31. Kamyab, F., Amini, M., Sheykhha, S., Hasanpour, M., & Jalali, M. M. (2016). Demand response program in smart grid using supply function bidding mechanism. *IEEE Transactions on Smart Grid, 7*(3), 1277–1284.
32. Lambiotte, R., Blondel, V. D., De Kerchove, C., Huens, E., Prieur, C., Smoreda, Z., et al. (2008). Geographical dispersal of mobile communication networks. *Physica A: Statistical Mechanics and Its Applications, 387*(21), 5317–5325.
33. Longo, G., & Montévil, M. (2012). The inert vs. the living state of matter: extended criticality, time geometry, anti-entropy–An overview. *Frontiers in Physiology, 3*, 39.
34. Longo, G., Montévil, M., Sonnenschein, C., & Soto, A. M. (2015). In search of principles for a theory of organisms. *Journal of Biosciences, 40*(5), 955–968.
35. Maldacena, J. (1999). The large-n limit of superconformal field theories and supergravity. *International Journal of Theoretical Physics, 38*(4), 1113–1133.
36. Manfredi, P., & D'Onofrio, A. (2013). *Modeling the interplay between human behavior and the spread of infectious diseases*. Berlin: Springer Science & Business Media.
37. Maslov, S. & Ispolatov, I. (2007). Propagation of large concentration changes in reversible protein-binding networks. *Proceedings of the National Academy of Sciences of the United States of America, 104*(34), 13655–13660.
38. Mistani, P., et al. (in preparation) *Syndemic control by social feedback*.
39. Mohammadi, A., & Dehghani, M. J. (2014). Spectrum allocation using fuzzy logic with optimal power in wireless network. In *2014 4th International eConference on Computer and Knowledge Engineering (ICCKE)* (pp. 532–536). IEEE.
40. Mohammadi, A., Dehghani, M., & Ghazizadeh, E. (2018). Game theoretic spectrum allocation in femtocell networks for smart electric distribution grids. *Energies, 11*(7), 1635.
41. Mohammadi, A., Mehrtash, M., & Kargarian, A. (2018). Diagonal quadratic approximation for decentralized collaborative TSO+ DSO optimal power flow. In *IEEE Transactions on Smart Grid*, 2018.
42. Molinero, C., Murcio, R., & Arcaute, E. (2017). The angular nature of road networks. *Scientific Reports, 7*(1), 4312.
43. Mora, T., & Bialek, W. (2011). Are biological systems poised at criticality? *Journal of Statistical Physics, 144*(2), 268–302.
44. Newman, M. E. (2003). The structure and function of complex networks. *SIAM Review, 45*(2), 167–256.
45. Nicosia, V., & Latora, V. (2015). Measuring and modeling correlations in multiplex networks. *Physical Review E, 92*(3), 032805.
46. Orús, R. (2014). A practical introduction to tensor networks: Matrix product states and projected entangled pair states. *Annals of Physics, 349*, 117–158 (2014).
47. Östlund, S., & Rommer, S. (1995). Thermodynamic limit of density matrix renormalization. *Physical Review Letters, 75*(19), 3537.
48. Rommer, S., & Östlund, S. (1997). Class of ansatz wave functions for one-dimensional spin systems and their relation to the density matrix renormalization group. *Physical Review B, 55*(4), 2164.
49. Schneidman, E., Berry II, M. J., Segev, R., & Bialek, W. (2006). Weak pairwise correlations imply strongly correlated network states in a neural population. *Nature, 440*(7087), 1007.
50. Shi, Y.-Y., Duan, L.-M., & Vidal, G. (2006). Classical simulation of quantum many-body systems with a tree tensor network. *Physical Review A, 74*(2), 022320.

51. Si, T. (2006). *Game theory and topological phase transition* (2006). arXiv preprint cond-mat/0601014.
52. Sornette, D. (2006). *Critical phenomena in natural sciences: Chaos, fractals, selforganization and disorder: Concepts and tools*. Berlin: Springer Science & Business Media.
53. Srednicki, M. (1993). Entropy and area. *Physical Review Letters, 71*(5), 666.
54. Sumpter, D. J. (2006). The principles of collective animal behaviour. *Philosophical Transactions of the Royal Society B: Biological Sciences, 361*(1465), 5–22.
55. Tkačik, G., Mora, T., Marre, O., Amodei, D., Palmer, S. E., Berry, M. J., et al. (2015). Thermodynamics and signatures of criticality in a network of neurons. *Proceedings of the National Academy of Sciences of the United States of America, 112*(37), 11508–11513.
56. Verstraete, F., & Cirac, J. I. (2004). *Renormalization algorithms for quantum-many body systems in two and higher dimensions*. arXiv preprint cond-mat/0407066.
57. Verstraete, F., Murg, V., & Cirac, J. I. (2008). Matrix product states, projected entangled pair states, and variational renormalization group methods for quantum spin systems. *Advances in Physics, 57*(2), 143–224 (2008).
58. Vidal, G. (2007). Entanglement renormalization. *Physical Review Letters, 99*(22), 220405 (2007).
59. Wang, Z., Wang, L., Szolnoki, A., & Perc, M. (2015). Evolutionary games on multilayer networks: A colloquium. *The European Physical Journal B, 88*(5), 124.
60. Wilde, M. M. (2013). *Quantum information theory*. Cambridge: Cambridge University Press.

Chapter 5
Tensor Network Renormalization as an Ultra-calculus for Complex System Dynamics

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> *"The belief on the part of many that the renormalisability of the universe is a constraint on an underlying Theory of Everything rather than an emergent property is nothing but an unfalsifiable article of faith."* Laughlin and Pines [32]

Introduction

Overview

In this chapter, following the previous one, we briefly present the modern approach to real-space renormalization group (RG) theory based on tensor network formulations which was developed during the last two decades. The aim of this sequel is to suggest a novel framework based on tensor networks in order to find the fixed points of complex systems via coarse-graining. The main result of RG is that it provides a systematic way to study the collective dynamics of a large ensemble of elements that interact according to a complex underlying network topology. RG explicitly seeks the fixed points of the complex system in the space of interactions and unravels the universality class of the complex system as well as calculates a plethora of important observables. We hope that tensor networks can particularly

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pave the way for better understanding of the sustainable interdependent networks [1] through proposing efficient computational strategies and discovering insightful features of the network behaviors.

Hierarchy of Realities in Complex Systems

Complex systems are collections of elements that interact in many ways and become a unity owing to their shared characteristics as a whole. These systems demonstrate emergent phenomena [42], i.e. novel and robust behaviors of a system that appear at the limit of some parameter in the system [5, 6]. Here we emphasize that emergence is a feature of the system as a whole and not associated with the details of individual elements. We emphasize that emergent properties appear at different scales and are real in their own right. These levels of reality, *i.e. set of properties of elements plus their interaction rules*, are independent of the details of the lower levels. In this section we will present historical examples to clarify this hierarchy of realities in complex systems.

Condensed Matter Physics The earliest hard-core scientific discipline to confront the issue of emergence is of course condensed matter physics where attempts to apply quantum mechanics to many-body systems have been historically made. For instance, it has been shown that the classical concept of molecular structure is not trivially compatible with quantum mechanics. For example, [15] have suggested that symmetric molecules such as AsH_3 are, in contrast to a naive application of quantum mechanics, localized in one of their configurations due to the perturbations caused by the environment. In this view, molecular structures are emergent and cannot be understood merely by solving Schrodinger's equation for the nuclei and electrons in the molecule, but rather they emerge as a result of an interplay with environmental effects.

Fluid Dynamics In 1986, Frisch et al. [25] have proposed a lattice-gas automata model that reproduces the Navier-Stokes equation at macro-scale. This model represents the microscopic world in at least two *un-realistic* ways: (1) particles move according to probabilistic rules and not according to the deterministic laws of classical mechanics, and (2) every particle moves on an underlying lattice with a velocity chosen from a limited set of discrete values ignorant to all the continuous possible values they can take. The astonishing aspect about this model is that even though it makes very crude approximations to not only the properties of the constituent particles but also their interactions, it still succeeds to reproduce the governing equations of motion at the large scales. This example demonstrates to what degree the microscopic details of a system could be irrelevant to the collective behavior of the system as a whole. This demonstrates how the multitude of the underlying degrees of freedom of a system is an independent world when observed at different length-scales. These are independent levels of reality.

Material Science Epitaxial growth is a complex, multiscale process in which a material is deposited on top of another one and conforms to the crystalline orientation of the substrate. Many physical processes occur during epitaxial growth including nucleation, growth, and coalescence of two-dimensional islands. Close to thermodynamic equilibrium, homoepitaxial growth proceeds atomic layer by atomic layer. However, growth is far from equilibrium for many homoepitaxial systems, and in particular, multilayer growth may become unstable which leads to formation of mounds. Mistani et al. [39] have successfully reproduced the multiscale features of epitaxial growth using the island dynamics model (IDM) [9, 26] which is essentially derived by coarse-graining of the atomistic dynamics in the lateral directions and retainment of atomistic detail in the growth direction.

The observed novel behaviors at larger length-scales demonstrate an example of emergent phenomena in this case. Importantly, the fact that the large-scale statistics of the epitaxial system are reproduced in agreement with experiments, while removing small-scale details through a coarse-graining procedure, is another example where a new reality appears regardless of the details of the elements. We also emphasize that multi-scale simulations are the only viable approach to investigating this class of emergent phenomena.

Biology Furthermore, this neutrality of the higher level behavior to the details of the lower level description has also been found in biological experiments of Wegsheid et al. [57]. They perform in vivo experiments on bacteria *Escherichia coli* and *Bacillus subtilis* that have very distinct three dimensional architecture, as well as biogenesis, biochemical/biophysical properties and enzyme function in vitro. However, they observe that structural type A and B bacterial ribonuclease P (RNase P) RNAs can fully replace each other in vivo despite their many reported differences in vitro.

Cell Aggregates Mistani et al. [40] have successfully reproduced the multiscale features of a complex cell aggregate (i.e.composing a sample tissue) under an external electric field. The overall result of the nonlinear interactions among tens of thousands of cells and the electric field leads to emergent phenomena for the tissue response such as the collective permeabilization pattern or the overall impedance of the tissue that are independent of the micro-scale details of the cells in the aggregate.

Carcinogenesis Another intriguing field of active research exploiting complex systems is *carcinogenesis*, i.e. or identifying the causes of cancer. Recent advances in the research on carcinogenesis has proposed to replace the century old Somatic Mutation Theory (SMT), which perceives genetic mutations as the cause for cancer, with Tissue Organization Field Theory (TOFT), which considers carcinogenesis as "development gone awry" [2]. TOFT is an exciting testbed whose success or failure will both be fruitful in a broader pursuit of a unifying "theory of organisms" [35, 55, 56]. While TOFT is a holistic theory, SMT is a reductionist version. This is because TOFT identifies disruptions to the interactions with the cell environment as the cause for carcinogenesis [2]. As summarized in [2], these disruptions can occur in different types of interactions: intercellular chemical signals, mechanical forces, and bioelectric changes.

Morphogenesis Furthermore ample experimental evidence suggests that electric fields can regulate pattern formation in biological organisms [29, 33, 36–38, 48]. For example, in the case of cancer as in the above paragraph, [13] have shown that tumor suppression is governed by the overall bioelectric state of the tissue. Or even more interestingly, Pietak et al. [47] have recently shown the axial transmembrane potential gradient along the planarian flatworms plays a key role in their regenerative process. These holistic frameworks not only provide novel paradigms to treat the issue of morphogenesis but also can help to reveal new rules of life, and consequently suggest novel methods to induce changes to or normalize abnormalities in complex systems. For a comprehensive review of this matter in the case of cancer, look at [12].

Among these examples we notice a repeating theme for what we call emergent: the novel behaviors that these systems exhibit at larger scales. There is a vast literature on reduction and emergence. However, in these chapters we attempt to follow Jeremy Butterfield's reconciliation of this issue to adopt a Nagelian view to reduction (as deduction accompanied with appropriate auxiliary definitions) and understand emergence as novel and robust behaviors (or theories) that appear at some limits of the descriptive theories. Particularly, Butterfield [5] combined emergence and reduction by taking one theory as the limit of another in some parameter, such as number of degrees of freedom or length-scale.

It is very remarkable to assert that in Butterfield's view reduction and emergence are independent and compatible notions, i.e. both can occur simultaneously. Furthermore, Butterfield (2013) has shown that renormalization in the case of quantum field theory reflects a unified family of Nagelian reductions. Hence, we must clarify that we treat renormalization as a procedure to deduce emergent behaviors that are also reductive.

In the case of Renormalization Group theory, we are considering situations where novel behaviors arise at the limit of large length-scales, when $L \to \infty$. For a philosophical discussion, see [7]. We should warn that neither this characterization necessarily generalizes to all instances of emergence (for example look at [24]), nor does renormalization provide a sufficient methodology to find emergent theories in all cases. However, this approach provides a viable means to investigate the class of novel behaviors that arise at the large limits of systems.

To understand the different levels of reality we introduce the powerful machinery of *renormalization group (RG)* that essentially transforms the lower-level realities to the higher-level realities as they manifest in complex systems by identifying and removing the irrelevant aspects of the lower levels. In the hierarchy of realities, RG is a ladder that reconciles different levels of complex systems and reveals their ultimate reality hidden at their largest scales.

The novelty of this sequel is to suggest the application of tensor network representation and renormalization to the case of interdependent networks. Especially where nodes can take many different states, and interact in many different ways.

Renormalization Group and Effective Theories

Complex systems exhibit a spectrum of effective theories when observed at different scales. Renormalization Group (RG) method is a mathematical apparatus to specify the coarse-grained functionality of complex systems and find the universal behavior of the system in the neighborhood of its critical fixed points in the space of possible theories. RG achieves this by identifying and removing the irrelevant behaviors of the system at lower scales in order to derive effective theories at larger scales.

Historically, it was around 1950s when the idea of renormalization appeared in the work of Dyson, Feynman, Schwinger, and Tomonaga [17, 18] as a criterion to select valid theories in order to avoid the problem of infinities in quantum electrodynamics. After two decades, around 1970s, Wilson [61–63], Kadanoff [30], Fisher [23], and others introduced a different version of RG where the core idea was to distinguish between the relevant and irrelevant interactions among the particles, such that non-renormalizable interactions do not contribute to the lower energies accessible to physical processes (for an illuminating discussion, we refer to [7, 8]), i.e. lower energies correspond to larger length-scales.

In essence, RG is a mathematical apparatus that transforms the lower-level realities to the higher-level realities as they manifest in complex systems by identifying and removing the irrelevant quantities [49]. A cartoon picture of an RG transformation is illustrated in Fig. 5.1. For instance, in the class of phenomena described by the stochastic Navier-Stokes equation quantities such as viscosity, mass, and noise couplings grow with increasing length-scale, hence they are examples of *relevant* parameters [44, 46]. RG is perhaps the most powerful idea to unravel the relationships among effective theories at different levels of reality [63]. During the past half a century, RG has significantly contributed to many disciplines of physics such as quantum field theory, phase transitions and critical phenomena in statistical physics, universality, turbulence, etc., as well as fundamental philosophical impact on the notion of reductionism [8].

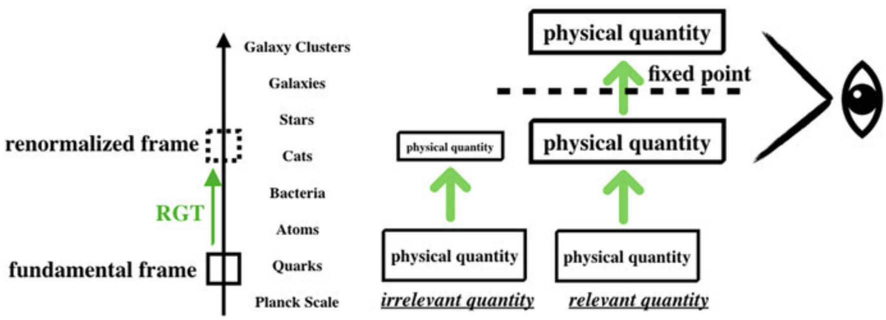

Fig. 5.1 Renormalization Group (RG) transformation of the observational frame (adapted from [49])

Renormalization Group Theory in a Nutshell

Basically, RG starts from a microscale model for the interactions; i.e. interactions are identified by some coupling constants represented as $(\mathrm{K}_1, \ldots, \mathrm{K}_\mathrm{N})$. between the elements of the complex system and seeks the variations of these constants at coarser resolutions. Hence, RG captures the evolution of coupling constants with scale. The dependence of couplings on scale originated from Leo P. Kadanoff in 1966 [30] and was later elaborated by Kenneth G. Wilson who computed the exact dependence and cast Kadanoff's argument in differential form [61, 63].

The vector of coupling constants *runs* through the "space of theories" along a trajectory, i.e. space of theories is spanned by the coupling constants in which every point identifies the parameters of a Hamiltonian. Furthermore, this trajectory can be conceived as a dynamical system that evolves with increasing the logarithm of length-scale via coarse-graining. In this regard, RG is the coarse-graining operator that evolves the dynamical system and determines the couplings of the original model at larger scales [7, 8, 10, 58].

Formally, one can define the renormalization group transformation, R_b, as [27]:

$$\vec{K}^{(n)} = R_b \vec{K}^{(n-1)}, \text{ and } b > 1, \tag{5.1}$$

where b is the coarsening scale factor. As a result, one RG iteration transforms the generic hamiltonian $\mathcal{H}$ to $\mathcal{H}'$:

$$\begin{aligned}\text{Original Hamiltonian}: \mathcal{H}_\mathrm{N} &= NK_0 + h\sum_i S_i + K_1 \sum_{ij} S_i S_j \\ &+ K_2 \sum_{ijk} S_i S_j S_k + \ldots, \\ \text{Renormalized Hamiltonian}: \mathcal{H}'_{\mathrm{N}'} &= N'K'_0 + h'\sum_i S'_i + K'_1 \sum_{ij} S'_i S'_j \\ &+ K'_2 \sum_{ijk} S'_i S'_j S'_k + \ldots,\end{aligned}$$

where $N' = N/b^d$ with d being the dimension of configuration space. Furthermore, the exponential reduction in the number of irrelevant degrees of freedom from the system is the core utility of the renormalization group theory. Note that in this procedure even if the original hamiltonian does not exhibit any three element interaction, $K_2 = 0$, however after renormalization we may end up with a three block interaction with $K'_2 \neq 0$. We also emphasize that such general form for the hamiltonian of a many-body system on a lattice inherently encapsulates contributions from the multitude of interactions among the constituents.

The set of all trajectories in the space of couplings produces a *renormalization group flow*. Also as scale increases, the coupling vector traces a trajectory and if renormalizable will be eventually attracted to a *fixed point*. At fixed points,

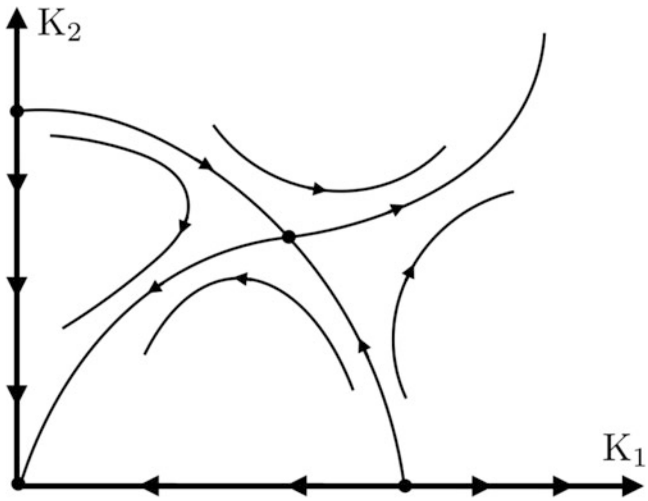

Fig. 5.2 A cartoon illustration of flow diagram of Ising model with nearest neighbor and next nearest neighbor interactions [27]. K_1 is the coupling constant with the nearest neighbor and K_2 is the coupling constant with the next nearest neighbor

the system becomes *scale invariant*, i.e. changing the scale doesn't change the properties of the system anymore, or:

$$\vec{K}^* = R_b \vec{K}^*, \tag{5.2}$$

The final fixed point of the system depends on the initial values of the couplings in this space which motivates the notion of *basin of attraction* for each fixed point. For example, Fig. 5.2 illustrates a slice of the three-dimensional space of couplings at $h = 0$ plane for a 2D Ising model with next nearest neighbor, $n.n.n$, interactions in an external magnetic field. The Hamiltonian for this system reads:

$$\mathcal{H} = K_1 \sum_{<ij>} S_i S_j + K_2 \sum_{ij=n.n.n} S_i S_j + h \sum_i S_i \tag{5.3}$$

where K_1 and K_2 are the coupling constants and h is the external magnetic field.

It is important to emphasize that despite finding effective couplings, RG also provides differential equations for the probability distribution functions for the system or the n-point correlation functions as other collaterals. For example, the two-point correlation function is of utmost significance when looking for phase transitions in complex systems. Also the maximal values for the two-point correlation function can be used to determine the clustering length-scales in complex systems such as characteristic length-scales for structures in the Universe and perhaps in biological systems [16, 46].

To illustrate some of the possible outcomes of RG, let us consider the standard example of a spin system. For an Ising system we define the reduced temperature as:

$$t = \frac{T - T_c}{T_c}$$

In the absence of external magnetic field in the vicinity of critical points of the system the magnetic susceptibility and specific heats read:

$$\chi \sim |t|^{-\gamma}, \ C_H \sim C_M \sim |t|^{-\alpha}$$

and the average spin, $\bar{S} =< S >$, for $h = 0$ and $h \neq 0$ reads respectively:

$$\bar{S} \sim |t|^{\beta},$$
$$|h| \sim |\bar{S}|^{\delta},$$

Furthermore, for small t the correlation length-scales as:

$$\xi \sim |t|^{-\nu}, \ \text{and}\ \nu = \frac{2-\alpha}{d}.$$

where d is the space dimension. The two-point correlation function, C_2, effectively determines the correlation length, ξ, for the system under consideration. For an Ising system it reads:

$$C_2(r, t) = \frac{1}{r^{d-2+\eta}} C^*(r/\xi).$$

in which $C^*(x) =$ constant for $x << 1$, and decays exponentially otherwise, $C^* = \exp(-x)$. The critical exponents are:

$$(2\text{D}) : \gamma = 7/4, \ \alpha = 0, \ \beta = 1/8, \ \delta = 15, \ \eta = 1/4, \ \nu = 1,$$
$$(3\text{D}) : \gamma \approx 1.24, \ \alpha \approx 0.10, \ \beta \approx 0.33, \ \delta \approx 4.75, \ \eta = 0.03 - 0.05, \ \nu \approx 0.63.$$

Under RG, the correlation length transforms according to:

$$\xi[K'] = \xi[K]/b,$$
$$\xi[K^*] = \xi[K^*]/b,$$

so at the fixed point, the correlation length is either zero, a *trivial fixed point*, or infinity, a *critical fixed point*. The trivial fixed points determine the global structure of the phase diagram for the system while the critical fixed points determine the *universality class* for a given system. The asymptotic dynamics of the system's observables in the vicinity of the critical fixed points are given by some universal scaling laws and critical exponents. We note that, in general, critical exponents are determined by only the symmetries and dimension of the system.

In this brief subsection we only introduced the RG theory in order to motivate the next topics. For a thorough discussion of RG theory, we refer the reader to Nigel Goldenfeld's lectures on phase transition and renormalization group [27] as a standard reference.

Asymptotic Behavior of Complex Systems

Complex systems can exhibit a variety of behaviors when observed at large scales. Most notable ones include self-similar and hierarchical structures. In this subsection we will demonstrate that the two-point correlation function, $C_2(r)$, is a good measure to classify the asymptotic behavior of complex systems. This should also motivate the application of RG methods to studies of complex systems. Here we also mention the morphological information encoded in such correlation functions empowers the accurate reconstruction of random realizations of the system under investigation. This has been shown by Yeong and Torquato [65]. Their procedure is generally applicable to multidimensional, multiphase, and anisotropic structures.

Self-similar Structure

Let's consider a rather general form for *real* two-point correlation function far from criticality:

$$C_2(r) \sim \frac{e^{-r/\xi}}{r^p} \tag{5.4}$$

$C_2(r)$ essentially demonstrates the correlation between two elements at a distance r. In this definition ξ is the correlation length, which determines how far any two elements of the system can feel each other. This effectively allows one to partition the system into subsystems of size ξ. However, at a critical point phase transition occurs during which the system is scale-invariant. Consequently, this resembles itself as the divergence of the correlation length, $\xi \to \infty$, i.e. all constituents are correlated. Hence, the exponential term vanishes and complex systems at criticality exhibit power-law behavior for the two-point correlation function:

$$C_2(r) \sim r^{-p} \tag{5.5}$$

Power-law scalings are the hallmark of self-similar systems at criticality. Despite complex networks this behavior has been observed in many natural systems [41]. We refer to the technical paper by [14] for dozens of examples of power-law governed systems in nature as well as the statistical methods to detect such behaviors. Another interesting example is the scale-invariance of natural images [51] which can be used as ansatz for the structure of images to be detected in machine-learning algorithm design.

Hierarchical Structure

A different type of behavior is hierarchical behavior. Hierarchic systems are an agglomeration of interdependent subsystems that exhibit ordered behaviors in their own right. As defined by Simon [53], each subsystem at any level of the hierarchy is itself hierarchical until we reach some elementary subsystem. By this definition, many complex systems are actually hierarchical: quarks, nuclei, atoms, molecules, cells, tissues, organs, living organisms, social organizations, scientific organizations, ecologies, all the way to large structures in the universe such as galaxies that are subsystems of clusters of galaxies and so on. Look at Fig. 5.1.

Hierarchies typically occur in *out-of-equilibrium* many-component systems and can be captured via coarse graining. Hierarchical systems are usually resulted from some sort of *phase transition* from a non-hierarchical state to a hierarchical one [11], see Fig. 5.3. As was demonstrated by Dominguez et al. [16] and Perez-Mercader [46] the hierarchical behavior can be attributed to the emergence of *complex fixed points* in the space of couplings that subsequently leads to a complex component for the correlation functions. Furthermore, the *reality of probabilities* along with a tendency for *maximal correlations* among constituents translate into a power-law damped oscillating two-point correlation function with a log-periodic argument, whose maxima are in surprising agreement with scales of the hierarchical structures in the Universe.

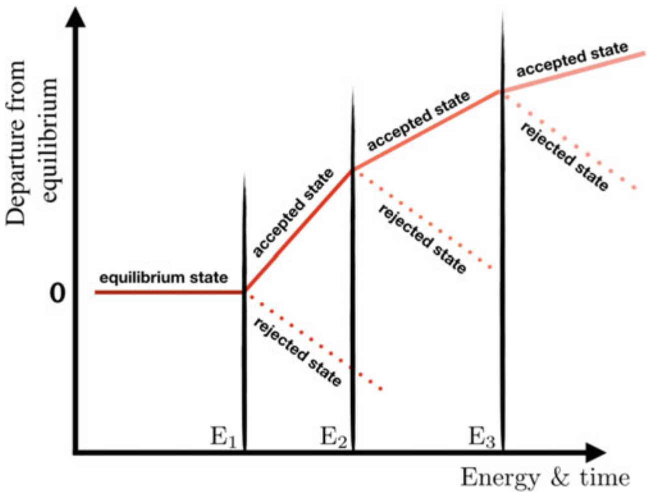

Fig. 5.3 The evolution of an open system and the extent of its departure from equilibrium. Through an evolutionary process, implied from the time axis, free energy flows through the open system until at certain critical energies, depicted by E_c, system bifurcates to non-equilibrium states. The acquired state and hence the subsequent structure of the system is determined by the stochasticity present in the environment. This figure is adapted from [11]

In the case of structures in the Universe, [46] argued that the scaling law for an observable of a system can be generically cast into the following form:

$$f(x) = \frac{1}{a} f(bx), \tag{5.6}$$

where b is the scaling factor as mentioned earlier. The general solution of this equation reads:

$$f(x) \sim x^{\sigma},$$
$$\sigma = \frac{\log a}{\log b} + i\frac{2n\pi}{\log b}, \quad \text{where } n = 0, 1, 2, \ldots$$

After coarse graining the Navier-Stokes equation for a non-equilibrium stirred fluid with a damping proportional to velocity, which is assumed as a model for the dynamics of the structure formation in the Universe, one derives the following behavior for the two-point correlation function [46]:

$$C_2(r, t; r', t) \sim |r - r'|^{2\alpha}. \cos\left(\beta + 2\zeta \log\left(\frac{|r - r'|}{r_0}\right)\right) \tag{5.7}$$

whose maxima occur at the following length-scales:

$$|r_n - r'| = r_0. \exp\left(\frac{\arctan(\alpha/\zeta) - \beta}{2\zeta}\right). \exp\left(\frac{n\pi}{2\zeta}\right). \tag{5.8}$$

or

$$|r_n - r'| \sim b^n. \tag{5.9}$$

Here we note that the scaling factor b is exactly computable from RG. This relation, for $b \sim 0.9$, perfectly matches the scaling law for the sizes of the hierarchy of structures in the observed universe from molecular clouds to superclusters of galaxies.

Network Renormalization

In the previous section we showed application of RG to determine the structural correlations as they appear in complex systems. Now we turn our attention to another application of RG to characterize the dynamics of complex networks in the vicinity of their fixed points. Our aim is to demonstrate how RG can provide a means to assess dynamics of complex systems by investigating the stability conditions of their fixed points.

Rozenfeld et al. [50] have applied the RG theory to complex networks and demonstrated the existence of a small-world-fractal transition by identifying the fixed points of the graph and their dependence on the degree of long-range interactions within the network.

The *small world* feature of scale-free networks corresponds to the logarithmic scaling of the average diameter of the network as $\bar{r} \sim \log(N_0)$ with N_0 being the total number of nodes in the network. However, a *fractal* feature appears at finite scales of the network and corresponds to a different relation where diameter scales with $\bar{r} \sim N_0^{1/d_B}$. Here d_B is the fractal dimension or box dimension up to the global scale of the network where small world behavior is recovered. We note that this is different than d_f which is determined by choosing a seed node and a cluster of nodes centered on this node with a minimum distance l is calculated. The average number of nodes within these clusters determines the fractal cluster dimension, d_f, by $< M > \sim l^{d_f}$. [54] have shown for complex small world networks $d_f \to \infty$. However, for homogenous networks, with narrow degree distribution, one can assume $d_B = d_f$.

In their approach, Rozenfeld et al. deploy the “box covering” renormalization method introduced by Song et al. [54]. This procedure starts by choosing a scaling factor b, and proceeds by partitioning the whole network into non-overlapping tiles whose maximum diameter is less than b. Then each tile is replaced with a “supernode” and is connected to other “supernodes” only if there has been at least one link between their progenitor boxes. This procedure is schematically shown in Fig. 5.4. This is equivalent to an RG transformation, R_b, where an initial network G_0 is successively coarse-grained to a new network G_b:

$$[G_b] = R_b[G_0], \tag{5.10}$$

In the general case, successive iterations of RG transformation will eventually generate a scale-invariant version of the network, G^*, which:

$$[G^*] = R_b[G^*]. \tag{5.11}$$

G^* is the fixed point of the RG transformation for the given system. Furthermore, if G_0 exhibits fractal structure its topological features will not change through coarse graining.

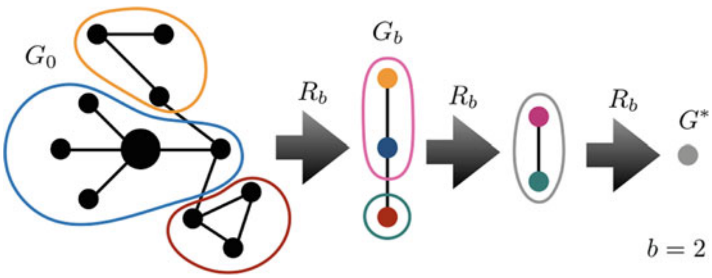

Fig. 5.4 Box covering RG technique

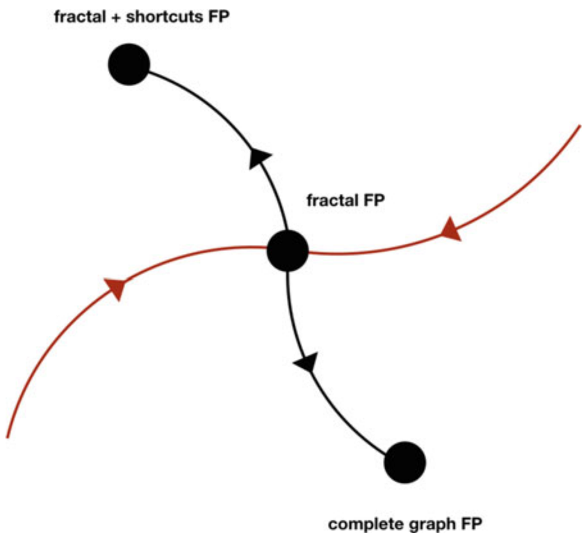

Fig. 5.5 The three fixed points of small-world-fractal networks and their stabilities

If one adds shortcuts to the initial fractal G_0 according to a certain power law $P(r) \sim r^{-\alpha}$ to build G', Rozenfeld et al. have shown that depending on the exponent α, RG procedure will coarse grain G' to G_0 or to a complete graph where all nodes are connected. Hence, G_0 and the complete graph are two fixed points in the space of networks. Further analysis reveals a third nontrivial stable fixed point consisting of the original network G_0 with highly probable shortcuts following $P(r) \sim 1 - \exp\left(-Ar^{-2d_B}\right)$. Figure 5.5 illustrates these fixed points and their stability. For more details, look at [50].

Tensor Renormalization

In the previous section we showed how simple implementations of RG provide invaluable information on the asymptotic behaviors of some complex systems. In this section, we introduce tensor renormalization techniques as an extension to the "box covering" technique in the previous section. This new formalism allows for consideration of more complex interactions among nodes in a network: which is demanded in the case of interdependent networks as well as in the case of having multiple states for each node.

Tensor networks are composed of intertwined tensors that are connected with shared indices. Every index in the tensor corresponds to the number of states of a statistical observable of an element. The number of possible states determines the *bond dimension* or χ and possible values for each index are drawn from $\{1, 2, \ldots, \chi\}$. Tensor network states are usually used to approximate the ground states of hamiltonians on a D-dimensional lattice. For example, consider the

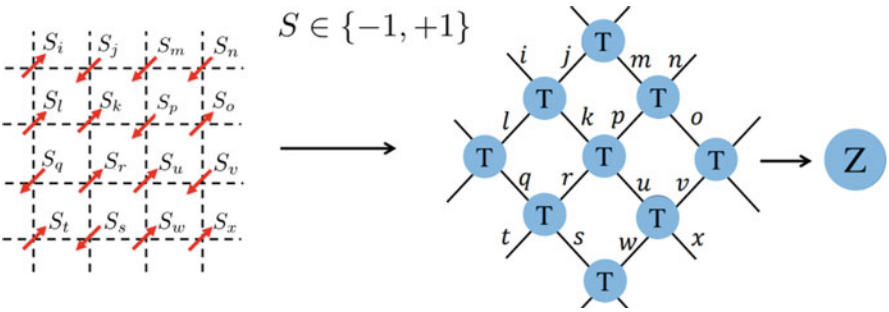

Fig. 5.6 A tensor network representation of a classical Ising model on a 2D lattice. The middle panel is the corresponding dual lattice for the original lattice. This image is adapted from [22]

simplest case of a classical Ising model on a 2D regular lattice as shown in Fig. 5.6: the *locality* constraint on the hamiltonian of the system justifies the partitioning of the system hamiltonian as the sum of blocks composed of only the neighbors that are in range for local interactions. In doing so one can write:

$$Z = e^{-\beta F} = \mathrm{Tr}_{\{S_i\}} e^{-\beta \sum_{\text{blocks}} \mathrm{H}_{\text{block}}} = \mathrm{Tr}_{\{S_i\}} \Pi_{\text{block}} e^{-\beta \mathrm{H}_{\text{block}}},$$

next, one can combine the interaction hamiltonians participating in each block to get the tensor representation of each block, i.e. the four-dimensional T tensors:

$$H(\{\sigma_i\}) = -\sum_{<i,j>} J S_i S_j,$$

$$T_{ijkl} = e^{\beta J (S_i S_j + S_j S_k + S_k S_l + S_l S_i)/2},$$

According to the specific interaction in the system one can find such tensor representation of the interactions. In terms of T, the generic equation for the partition function reads:

$$Z = e^{-\beta F} = \sum_{i,j,k,\ldots} \Pi\big(T_{ijkl}\big) = \mathrm{tTr}\big(\otimes_{\mathrm{x}=1}^{\mathrm{N}} \mathrm{T}\big). \tag{5.12}$$

where tTr is the tensor trace. By the observation that it is not a single spin that matters but the relative pairwise state of spins that contributes to the hamiltonian, one might equivalently use the dual lattice with defining a new variable $\sigma_{ij} = S_i S_j$ to characterize each *bond* instead of the nodes, Fig. 5.6. It is important to note that in this formulation the product of the four vertices around each loop is constrained to satisfy $\sigma_{ij}\sigma_{jk}\sigma_{kl}\sigma_{li} = 1$. This simplifies the fundamental tensor to:

$$T_{ijkl} = \frac{1 + \sigma_{ij}\sigma_{jk}\sigma_{kl}\sigma_{li}}{2} e^{\beta J (\sigma_{ij} + \sigma_{jk} + \sigma_{kl} + \sigma_{li})/2}.$$

As is clear in Fig. 5.6 each index explicitly corresponds to an element in the network. The basic operation of our interest is the renormalization transformation of a tensor network. However, it has been shown that explicit evaluation of Eq. (5.12) is NP-hard [52], this motivates advent of efficient approximate algorithms. Such transformations are essentially achieved by a *proper* coarse-graining procedure. A *proper* transformation not only preserves the free energy of the system but also must totally remove the short-ranged correlations/entanglements in the description of the system at each iteration.

As was mentioned earlier, a renormalization transformation R_b effectively transforms the vector of couplings $\vec{K}$ of the original hamiltonian to a coarse-grained set of couplings denoted by $\vec{K}'$:

$$\vec{K}' = R_b \vec{K}.$$

Each iteration of coarse-graining rescales the distance between neighboring lattice points by a factor b. One can analyze the correlations between couplings and their coarse-grained counterparts to characterize the renormalization flow around the *fixed points* $\vec{K}^*$:

$$G_{ij} = \frac{dK'_i}{dK_j}|_{\vec{K}^*},$$

The eigenvalues, λs, of G give rise to the critical exponents observed in the vicinity of the fixed points:

$$\lambda_\alpha \sim b^{d-x}.$$

where d is the dimension of the network and x is the critical exponent. An operator will contribute to the asymptotic behavior of the complex system as it converges to the fixed point only if its critical exponent satisfies $x < d$. In this case it is called a *relevant* operator but will be *irrelevant* otherwise [31].

In the next section we will briefly scratch on the surface of tensor renormalization group (TRG) as the simplest of such transformations which also serves as the backbone of the more recent methods. For a comprehensive overview of the real space renormalization methods in statistical mechanics, we refer to the reference by Efrati et al. [19]. For a recent and more pedagogical review, look at [4]. Especially a practical introduction to tensor networks is the one by Roman Orus [45].

Tensor Renormalization Group (TRG) Method and Correlation Function

There are many algorithms to properly renormalize a tensor network, for a review of these methods, we refer to [20]. In this section we only introduce the tensor renormalization group (TRG) introduced by Levin and Nave [34].

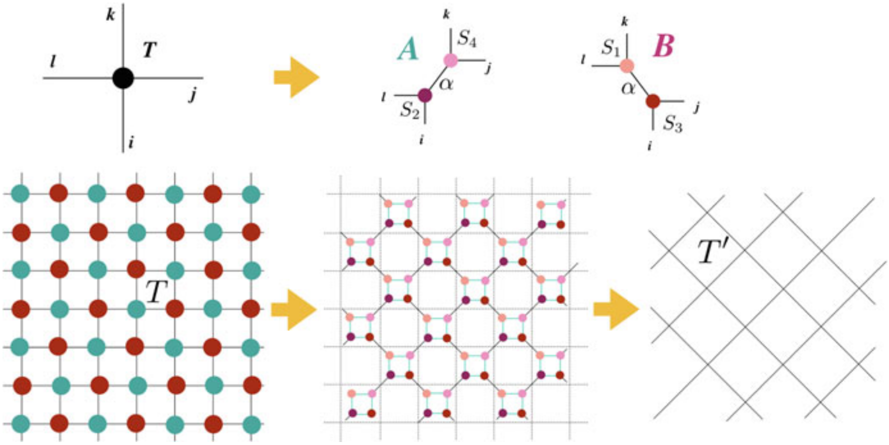

Fig. 5.7 Illustration of a TRG step for a rank four tensor network. Each sublattice is rewired according to the decompositions A or B shown in the above panel. Then, the cyan squares are decimated

TRG is a generalization of the celebrated DMRG method of Steven White [59, 60] for one-dimensional quantum many-body systems to higher dimensions. Basically, the TRG algorithm has two steps: rewiring and decimation, look at Fig. 5.7. In the rewiring step one decomposes each tensor T by either of two pairings of the four indices:

$$T^A_{(il),(jk)} = \sum_{\alpha=1}^{D^2} S_{2,il\alpha} S_{4,jk\alpha},$$

$$T^B_{(kl),(ij)} = \sum_{\alpha=1}^{D^2} S_{1,kl\alpha} S_{3,ij\alpha}.$$

we note that one shall not confuse these S tensors with spins in the lattice. Next, in the decimation step one can approximate S matrices using SVD decomposition of tensor T and only keeping $D' = \min(D^2, D_{\text{threshold}})$ largest singular values:

$$T^A_{(il),(jk)} = U\Sigma V^\dagger \approx \sum_{\alpha=1}^{D'} \left(\sqrt{\lambda_\alpha} U_{il,\alpha}\right)\left(\sqrt{\lambda_\alpha} V^\dagger_{jk,\alpha}\right),$$

$$T^B_{(kl),(ij)} = U\Sigma V^\dagger \approx \sum_{\alpha=1}^{D'} \left(\sqrt{\lambda_\alpha} U_{kl,\alpha}\right)\left(\sqrt{\lambda_\alpha} V^\dagger_{ij,\alpha}\right),$$

Eventually, the smaller plaquettes portrayed as cyan squares in Fig. 5.7 will be contracted, i.e. summed over their shared indices, in order to get the coarse-grained tensor T':

$$T'_{ijkl} = \sum_{\alpha,\beta,\gamma,\delta=1}^{D} S_{1,\alpha\delta i} S_{2,\alpha\beta j} S_{3,\beta\gamma k} S_{4,\gamma\delta l}.$$

Note that through this procedure the number of tensors has reduced by a factor of 4. It is important to appreciate that without the decimation step the bond dimension of the coarse-grained tensors grows exponentially and very quickly becomes computationally intractable. It is this step which determines the success of TRG to remove irrelevant correlations in the system.

This finalizes one iteration of TRG by defining the transformation $T \rightarrow T'$. Successive iterations produce the RG flow for the system until the flow converges to fixed points. For completeness we emphasize that the accuracy of TRG suffers in the vicinity of the critical points in the RG flow. This is a great challenge that prohibits accurate computation of fixed points which is the main goal of this chapter. The alternative algorithms that fix this problem are the Tensor Network Renormalization (TNR) algorithm [22] or alternatively the loop optimization for tensor network renormalization (Loop-TNR) algorithm [64] but we leave these methods to the interested reader.

As was first shown by Gu et al. [28] tensor renormalization groups can be used to compute correlation functions. For an explicit example, we refer to the work of [43] where they compute the correlation function for a 2D classical Ising system by introducing the "impurity" tensor [28] into the lattice. We conclude this section by recommending the reference by Evenbly and Vidal [21] to gain a fundamental perspective on correlations and their relationship to different families of tensor networks.

Conclusion

Traditional methods have long been used in order to study topology of complex networks, usually in pursuit of robustness of the network. However, dynamics of nodes in a network are also of significance when coupled to network architecture. In this spirit, renormalization group methods on tensor networks seem to be a promising avenue to discover the asymptotic behaviors of complex networks where nodes interact in many different ways.

Furthermore, the idea of using RG methods for studying complex systems has been advocated by many authors, among most recent ones are Bradde and Bialek [3] who have also shown its applicability on neural networks and financial markets. In this chapter we introduced the possibility to use tensor network renormalization methods to analyze asymptotic dynamics of natural networks via finding their fixed points in the space of models. This is in contrast to other dimensional reduction methods such as principal component analysis (PCA) that seek fixed points in the space of dynamical variables.

References

1. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks: From theory to application* (Vol. 145). Cham: Springer.
2. Baker, S. G. (2014). A cancer theory kerfuffle can lead to new lines of research. *Journal of the National Cancer Institute, 107*(2), dju405.
3. Bradde, S.& Bialek, W. (2017). PCA meets RG. *Journal of Statistical Physics, 167*(3–4), 462–475.
4. Bridgeman, J. C., & Chubb, C. T. (2017). Hand-waving and interpretive dance: An introductory course on tensor networks. *Journal of Physics A: Mathematical and Theoretical, 50*(22), 223001.
5. Butterfield, J. (2011a). Less is different: Emergence and reduction reconciled. *Foundations of Physics, 41*(6), 1065–1135.
6. Butterfield, J. (2011b). Emergence, reduction and supervenience: a varied landscape. *Foundations of Physics, 41*(6), 920–959.
7. Butterfield, J. (2014). Reduction, emergence, and renormalization. *The Journal of Philosophy, 111*(1), 5–49.
8. Butterfield, J., & Bouatta, N. (2015). Renormalization for philosophers. *Metaphysics in Contemporary Physics, 104*, 437–485.
9. Caflisch, R. E., Gyure, M., Merriman, B., Osher, S., Ratsch, C., Vvedensky, D., et al. (1999). Island dynamics and the level set method for epitaxial growth. *Applied Mathematics Letters, 12*(4), 13–22.
10. Cao, T. Y., & Schweber, S. S. (1993). The conceptual foundations and the philosophical aspects of renormalization theory. *Synthese, 97*(1), 33–108.
11. Chaisson, E. J., & Chaisson, E. (2002). *Cosmic evolution*. Cambridge: Harvard University Press.
12. Chernet, B., & Levin, M. (2013). Endogenous voltage potentials and the microenvironment: Bioelectric signals that reveal, induce and normalize cancer. *Journal of Clinical & Experimental Oncology, 2013*(Suppl. 1), S1-002.
13. Chernet, B. T., & Levin, M. (2014). Transmembrane voltage potential of somatic cells controls oncogene-mediated tumorigenesis at long-range. *Oncotarget, 5*(10), 3287.
14. Clauset, A., Shalizi, C. R., & Newman, M. E. (2009). Power-law distributions in empirical data. *SIAM Review, 51*(4), 661–703.
15. Claverie, P., & Jona-Lasinio, G. (1986). Instability of tunneling and the concept of molecular structure in quantum mechanics: The case of pyramidal molecules and the enantiomer problem. *Physical Review A, 33*(4), 2245.
16. Domínguez, A., Hochberg, D., Martín-García, J., Pérez-Mercader, J., & Schulman, L. (1999). *Dynamical scaling of matter density correlations in the universe: An application of the dynamical renormalization group*. Arxiv preprint astro-ph/9901208.
17. Dyson, F. J. (1949). The radiation theories of tomonaga, schwinger, and feynman. *Physical Review, 75*(3), 486.
18. Dyson, F. J. (1949). The s matrix in quantum electrodynamics. *Physical Review, 75*(11), 1736.
19. Efrati, E., Wang, Z., Kolan, A., & Kadanoff, L. P. (2014). Real-space renormalization in statistical mechanics. *Reviews of Modern Physics, 86*(2), 647.
20. Evenbly, G. (2017). Algorithms for tensor network renormalization. *Physical Review B, 95*(4), 045117.
21. Evenbly, G., & Vidal, G. (2011). Tensor network states and geometry. *Journal of Statistical Physics, 145*(4), 891–918.
22. Evenbly, G., & Vidal, G. (2015). Tensor network renormalization. *Physical Review letters, 115*(18), 180405.
23. Fisher, M. E. (1974). The renormalization group in the theory of critical behavior. *Reviews of Modern Physics, 46*(4), 597.

24. Franklin, A., & Knox, E. (2018). Emergence without limits: The case of phonons. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*.
25. Frisch, U., Hasslacher, & Pomeau, Lattice-gas automata for the navier-stokes equation. *Physical Review Letters, 56*(14), 1505.
26. Gibou, F., Ratsch, C., Gyure, M., Chen, S., & Caflisch, R. (2001). Rate equations and capture numbers with implicit islands correlations. *Physical Review B, 63*(11), 115401.
27. Goldenfeld, N. (2018). *Lectures on phase transitions and the renormalization group*. Boca Raton: CRC Press.
28. Gu, Z.-C., Levin, M., & Wen, X.-G.. Tensor-entanglement renormalization group approach as a unified method for symmetry breaking and topological phase transitions. *Physical Review B, 78*(20), 205116.
29. Jaffe, L. F., & Nuccitelli, R. (1977). Electrical controls of development. *Annual Review of Biophysics and Bioengineering, 6*(1), 445–476.
30. Kadanoff, L. P. (1966). Scaling laws for ising models near t (c). *Physics, 2*, 263–272.
31. Kadanoff, L. P., & Wegner, F. J. (1971). Some critical properties of the eight-vertex model. *Physical Review B, 4*(11), 3989.
32. Laughlin, R. B., & Pines, D. (2000). The theory of everything. *Proceedings of the National Academy of Sciences of the United States of America, 97*(1), 28–31.
33. Levin, M. (2007). Large-scale biophysics: Ion flows and regeneration. *Trends in Cell Biology, 17*(6), 261–270.
34. Levin, M., & Nave, C. P. (2007). Tensor renormalization group approach to two-dimensional classical lattice models. *Physical Review Letters, 99*(12), 120601.
35. Longo, G. (2017). The biological consequences of the computational world: Mathematical reflections on cancer biology (2017). arXiv preprint arXiv:1701.08085.
36. Lund, E. (1925). Experimental control of organic polarity by the electric current. V. The nature of the control of organic polarity by the electric current. *Journal of Experimental Zoology Part A: Ecological Genetics and Physiology, 41*(2), 155–190.
37. Lund, E. J. (1947). *Bioelectric fields and growth* (Vol. 64). Philadelphia: LWW.
38. Mathews, A. P. (1903). Electrical polarity in the hydroids. *American Journal of Physiology–Legacy Content, 8*(4), 294–299.
39. Mistani, P., Guittet, A., Bochkov, D., Schneider, J., Margetis, D., Ratsch, C., et al. (2018). The island dynamics model on parallel quadtree grids. *Journal of Computational Physics, 361*, 150–166.
40. Mistani, P., Guittet, A., Poignard, C., & Gibou, F. (February 2018). *A parallel voronoi-based approach for mesoscale simulations of cell aggregate electropermeabilization*. ArXiv e-prints.
41. Mora, T., & Bialek, W. (2011). Are biological systems poised at criticality? *Journal of Statistical Physics, 144*(2), 268–302.
42. Nagel, E., & Hawkins, D. (1961). The structure of science. *American Journal of Physics, 29*, 716.
43. Nakamoto, N., & Takeda, S. (2016). Computation of correlation functions by tensor renormalization group method. *Sciece Reports of Kanazawa University, 60*, 11–25
44. Onuki, A. (2002). *Phase transition dynamics*. Cambridge: Cambridge University Press.
45. Orús, R. (2014). A practical introduction to tensor networks: Matrix product states and projected entangled pair states. *Annals of Physics*, 349, 117–158.
46. Perez-Mercader, J. (2004). Coarsegraining, scaling and hierarchies. In *Nonextensive Entropy-Interdisciplinary Applications* (pp. 357–376). Oxford: Oxford University Press.
47. Pietak, A., & Levin, M. (2017). Bioelectric gene and reaction networks: computational modelling of genetic, biochemical and bioelectrical dynamics in pattern regulation. *Journal of the Royal Society Interface, 14*(134), 20170425 (2017).
48. Robertson, D., Miller, M. W., & Carstensen, E. L. (1981). Relationship of 60-hz electric-field parameters to the inhibition of growth ofpisum sativum roots. *Radiation and Environmental Biophysics, 19*(3), 227–233.

49. Rodriguez-Laguna, J. (2002). *Real space renormalization group techniques and applications*. arXiv preprint cond-mat/0207340.
50. Rozenfeld, H. D., Song, C., & Makse, H. A. (2010). Small-world to fractal transition in complex networks: A renormalization group approach. *Physical Review Letters, 104*(2), 025701.
51. Ruderman, D. L., & Bialek, W. (1994). Statistics of natural images: Scaling in the woods. In *Advances in Neural Information Processing Systems*, pp. 551–558.
52. Schuch, N., Wolf, M. M., Verstraete, F., & Cirac, J. I. (2007). Computational complexity of projected entangled pair states. *Physical Review Letters, 98*(14), 140506.
53. Simon, H. A. (1996). *The sciences of the artificial*.
54. Song, C., Havlin, S., & Makse, H. A. (2005). Self-similarity of complex networks. *Nature, 433*(7024), 392.
55. Soto, A. M., Longo, G., Miquel, P.-A., Montévil, M., Mossio, M., et al. (2016). Toward a theory of organisms: Three founding principles in search of a useful integration. *Progress in Biophysics and Molecular Biology, 122*(1), 77–82.
56. Soto, A. M., & Sonnenschein, C. (2011). The tissue organization field theory of cancer: A testable replacement for the somatic mutation theory. *Bioessays, 33*(5), 332–340.
57. Wegscheid, B., Condon, C., & Hartmann, R. K. (2006). Type a and b rnase p rnas are interchangeable in vivo despite substantial biophysical differences. *EMBO Reports, 7*(4), 411–417 (2006).
58. Weinberg, S. (1997). *What is quantum field theory, and what did we think it is*? arXiv preprint hep-th/9702027.
59. White, S. R. (1992). Density matrix formulation for quantum renormalization groups. *Physical Review Letters, 69*(19), 2863.
60. White, S. R. (1993). Density-matrix algorithms for quantum renormalization groups. *Physical Review B, 48*(14), 10345.
61. Wilson, K. G. (1971). Renormalization group and critical phenomena. I. Renormalization group and the kadanoff scaling picture. *Physical Review B, 4*(9), 3174.
62. Wilson, K. G. (1975). The renormalization group: Critical phenomena and the kondo problem. *Reviews of Modern Physics*, 47(4), 773.
63. Wilson, K. G., & Kogut, J. (1974). The renormalization group and the e expansion. *Physics Reports, 12*(2), 75–199.
64. Yang, S., Gu, Z.-C., & Wen, X.-G. (2017). Loop optimization for tensor network renormalization. *Physical Review Letters, 118*(11), 110504.
65. Yeong, C. L. Y., & Torquato, S. (1998). Reconstructing random media. *Physical Review E, 57*, 495–506.

Part II
Intelligent Transportation Networks

Chapter 6
Intelligent Transportation Systems in Future Smart Cities

Samaneh Khazraeian and Mohammed Hadi

Introduction

Overview

Intelligent transportation systems (ITS) are state-of-the-art applications to improve the transportation safety and mobility, as well as move towards an environmentally friendly system. ITS plays a pivotal role in future smart cities in terms of providing the users with more informed, safer, more secured, and cost-effective transportation system. To this end, ITS takes advantage of modern technologies including communication infrastructure to enable efficient data transfer among smart agents, advanced computational methods to deal with large-scale optimization problems, autonomous vehicles, electrified vehicles, connected vehicles, and intelligent traffic signals. In this chapter, we provide a comprehensive overview of some ITS technologies. Some of the recent methods to enable these technologies are introduced to pave the road for future researchers working in this area. To provide readers with case examples of ITS, two connected vehicle applications are elaborated in this chapter: queue warning and automatic incident detection. Queue warning systems are designed to inform the drivers about the back-of-queue (BOQ) location so that

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they brake safely and in a timely manner. An automatic incident detection (AID) system aims to detect incident occurrence automatically utilizing traffic data such as speed, volume, and occupancy.

Forecasting the driving patterns and the data provided by advanced traveler information systems that affects the traffic in transportation network flow is important in modernizing the transportation networks and enabling intelligent transportation systems (ITS). Sharing the predicted traffic conditions, they are able to make more optimal decisions while traveling. This will lead to traffic congestion reduction as well as increased efficiency of transportation by enhancing the utilization of the current assets [1]. In [2], authors proposed an algorithm that takes into account several effective parameters (e.g., waiting time, density of vehicles, and volume of traffic) to control the traffic in a real-time fashion based on the wirelessly collected data. Their method estimates the green light sequence as well as the duration of each green light. In [3] a route optimization method is proposed for electrified vehicles which considers variables from both power systems and transportation networks. In this approach, traffic conditions, electricity price for charging the battery, and behavioral preferences of drivers are considered while determining the optimal route from the given origin to the expected destination. A comprehensive introduction to the theoretical approaches for ITS applications is provided in [4]. These methods are not only for intelligent transportation networks, but also applicable to other smart infrastructure. Transportation networks are among crucial sustainable interdependent networks [5]. First, there is an increasing evolution towards modernizing these networks by deploying more electric vehicles [6]; second, they are considered as key players of future smart cities [7]; third, they involve several other networks such as power systems and communication networks. The interdependent aspects of power and transportation networks have been extensively studied in [2]. Further, the effect of electrified vehicle charging demand on the operation of power systems is investigated in [6].

More information about the performance measures, detection rate (DR), false alarm rate (FAR), and mean time to detect (MTTD), is provided in [8, 9].

Automatic Incident Detection

An automatic incident detection (AID) system aims to detect incident occurrence automatically utilizing traffic data such as speed, volume, and occupancy. An AID system has two components: a data collection system and an incident detection algorithm. The data collection system provides real-time traffic data such as speed, occupancy, and flow using data collection devices (e.g., point detectors, CCTV cameras, tag readers, Bluetooth). The collected data is analyzed through incident detection algorithms to declare the incident occurrence. The performance of incident detection algorithms is normally evaluated using three commonly used performance measures: detection rate (DR), false alarm rate (FAR),and mean time to detect

(MTTD) [8, 9]. DR is the ratio of number of correct detections by total number of actual incidents occurring in a time period and is shown in Eq. (6.1):

$$\text{DR} = \frac{\text{Number of correct detections}}{\text{Total number of incidents}} \times 100\% \tag{6.1}$$

Different researchers have defined different FARs for different purposes. $\text{FAR}_{\text{online}}$ and $\text{FAR}_{\text{off-line}}$ are the two main detentions found in the literature. $\text{FAR}_{\text{online}}$ is the percentage of the number of incorrect decisions by the total number of algorithm decisions (all the declared alarms) while $\text{FAR}_{\text{off-line}}$ is the ratio of algorithm incorrect decisions by the number of algorithm applications [10]:

$$\text{FAR}_{\text{online}} = \frac{\text{Number of incorrect detections}}{\text{Total number of algorithem decisions}} \times 100\% \tag{6.2}$$

$$\text{FAR}_{\text{off}-\text{line}} = \frac{\text{Number of incorrect detections}}{\text{Total number of algorithem decisions}} \times 100\% \tag{6.3}$$

MTTD is the difference between estimated incident time by the algorithm and the observed incident time which is shown in Eq. (6.4).

$$\text{MTTD} = \text{Estimated incident time} - \text{Observed incident time} \tag{6.4}$$

Generally, automatic incident detection methods are categorized into two main groups: point detector-based and probe-based algorithms. Most of the traditional automatic incident detection algorithms use point detector data to detect incidents. However, there are some disadvantages in using point detector data. The main drawback of the point detector-based methods is that they cannot detect the incident until the queue caused by the incident reaches the upstream detector [11], which may take a long time and even may never happen if the queues due to incidents are short or do not exist. These algorithms were also found to produce large numbers of false alarms [12–14]. Furthermore, these sensors cannot be deployed all over the network as they are expensive and they cannot cover the entire network. It is also difficult to realize the true traffic conditions, as sensors collect spot traffic data. Incidents may be detected more efficiently using travel time measurements collected by probes (e.g., Bluetooth, Wi-Fi, electronic toll tag readers, and GPS) as they have a wider roadway coverage. Further, spectrum allocation of wireless networks is important to ensure the energy-efficient communication [15]. Mohammadi et al. proposed a highly efficient approach to reduce the power consumption of communication networks using fuzzy logics [15]. Their approach has several advantages compared with the existing communication platforms and can be deployed for different applications such as intelligent transportation networks. A summary of the point detector-based and probe-based algorithm performance reviewed above and other algorithms are shown in Table 6.1.

Table 6.1 Summary of point detector-based and probe vehicle-based algorithm performances

Point detector-based algorithms [16]					
Algorithm name	*DR (%)*	*MTTD (min)*	*FAR (%)*	*Location*	
California	82	0.85	1.73	California, Chicago, Texas	
McMaster	68	2.2	0.0018	Minnesota	
Neural Networks	89	0.96	0.012	Modeling, Simulation, and Analysis (MSA)	
Low-Pass Filter [17]	80	4	0.3	Modeling	
DES (Double-Exponential Smoothing) [18]	92	0.7	1.87	Toronto	
Bayesian [19]	100	4	0	Modeling	
Probe-based algorithms					
Algorithm name	*Probe technology*	*Penetration rate*	*Environment type*	*Data requirement*	*MTTD*
MIT [20]	AVI/ETC	50%	MITSIM-based simulation	Travel time and headway by lane, lane switches, volume by lane	0.8 min
TTI [21]	Cellular probe system	5-min headway	Field in Houston, TX	Travel time	15 min
TRANSMIT [22]	AVI/ETC	1-min headway	Field in metropolitan NYC	Travel time	15 min
Waterloo [23]	AVI/ETC	10%	INTEGRATION-based simulation	Travel time	0.3 min
MOSES [11]	Mobile Sensor	5–50%	Paramics microsimulation	Travel time	12–4 min
DSRC-based method [24]	DSRC	30%	CORSIM microsimulation	Travel time	–2 to 4 min, reader spacing 2 miles –2.5 to 14 min reader, spacing 10
Bluetooth-based method [25]	Bluetooth	6%	Field in Oregon	Travel time and volume	Not reported
GPS-based method [26]	GPS	1%	AIMSUN microsimulation	Travel time	14.8 min

Methodology

This study tests two freeway incident detection methods based on connected vehicle data. The methods are based on the vehicle's acceleration estimated based on connected vehicle data. Due to the fact that the vehicle's acceleration after slowing at and then passing the incident location is always positive, the acceleration after the incident location was selected to identify the incident signature for the proposed methods.

The methods were tested using the VISSIM microscopic simulation tool. VISSIM was used to emulate incident occurring in a mixed connected vehicle and not connected vehicles in a traffic stream. The vehicle's trajectories produced by VISSIM were fed to the Trajectory Conversion Algorithm (TCA) tool, produced by the Federal Highway Administration (FHWA) (25) to emulate BSM messages generating from the simulation. Then, the generated BSM messages were input to the incident detection methods to investigate their performances. More description of the TCA tool is presented in the case study section. The subsection below provides more details about the tested methods.

Method I: The Average Acceleration Distribution Method

This method aims to detect the abnormality in the traffic conditions using a predefined threshold based on the acceptable probability of false alarms. In this method, the network is decomposed to m segments. Using historical data of connected vehicle measurements, the acceleration distribution is derived for each segment for no-incident conditions. Four different hypothesis testing resolutions of 30, 60, and 90 ft. were conducted and the results were compared. In this study, the distributions are derived using multiple VISSIM runs under no-incident condition. According to central limit theorem, the average of large number of iterates of a random variable, regardless of the underlying distribution, is approximately normally distributed. So, the average acceleration in each segment is normally distributed. This distribution changes when the traffic demand changes. Thus, different distributions need to be derived for different periods. In practice, the lengths of the periods can be done using clustering analysis or other statistical techniques. The focus of this chapter is incident detection during medium and high traffic demand (high and medium congestion) for the simple test networks. Thus, for each segment two distributions were developed based on VISSIM runs with no incident and considered to be adequate for the purpose of this study. The 95th percentile of the average acceleration rate in each segment m for the two congestion levels was selected as the threshold for incident detection Method I. This means that the probability of the false alarms was set at 5%. The process of calculating the thresholds was done off-line. To detect the incident in real time, in each time interval, the whole network was scanned. If a segment average acceleration was higher than the threshold, the segment was detected as an incident location.

Method II: The LRT-Based Method

As with Method I, the incident detection problem is converted to a hypothesis testing problem with the null hypothesis being no incident presence and the alternative hypothesis being incident presence. The purpose of the hypothesis testing is to decide whether an incident happened or not in a specific time and location in the network based on an observed set of measurements $\{x[0], x[1], \ldots, x[N-1]\}$, with each of these measurements representing the individual measurements ahead of the tested segment for potential incident occurrence. Based on our observation of acceleration rate measurements in VISSIM, the influence area of the incident is 150 ft. after the incident location. This 150 ft. is decomposed to n_{sig} sub-segments and for each sub-segment the distribution under the incident and no-incident conditions is derived. Each of the N measurements within this 150 ft. belongs to any of n_{sig} distributions. The length of each sub-segment was selected to be 15 ft. However the resolution for deriving the distributions (15 ft.) can be different from the hypothesis test segment resolution. The hypothesis test segment resolution was selected to be 30 ft. However, the hypothesis test segment resolution can be longer in the expense of losing the accuracy of identification of the exact incident location. To clarify, if the hypothesis test segment resolution is 150 ft. and one segment is detected to have incident in it, the exact location of the incident within this 150 ft. cannot be determined. It should be realized that in most applications, locating the incidents to within 150 ft. is sufficient.

Hypothesis testing is conducted by looking at the N measurements within the 150 ft. after the segment and utilizing the pre-stored distributions of the measurements with and without incidents for the n_{sig} segments. The threshold in the hypothesis testing is not fixed as in Method I and is updated for each segment at each time interval. Since the measurements are not uniformly distributed at all locations in all time step, the number of measurements for each hypothesis testing is not known beforehand. Furthermore, the relative distance of the measurements to the respective location of the hypothesis testing is also unknown beforehand. Therefore the utilized incident detection algorithm is an adaptive detector that changes its form (test statistic) according to the number of available measurements and the relative distance of them to the respective hypothesis location. Detector form means the way to process the data and come up with a test statistic to compare it with a threshold. To clarify the methodology, suppose we are testing the ith segment of the network at time interval t. Measurements within 150 ft. after segment ith during time t are processed (using Eq. (6.7)) and compared with a threshold which is calculated using Eq. (6.8). According to Neyman-Pearson Theorem [27], in order to maximize the probability of detection (P_D) for a given probability of false alarm:

$(P_{FA}) = \alpha$, we accept H_1 if

$$L(X) = \frac{P\left(X;\, H_1\right)}{P\left(X;\, H_0\right)} > \gamma \tag{6.5}$$

where

X is the measurement vector.

$L(X)$ is the likelihood ratio that determines the likelihood of each X belonging to H_1 versus the likelihood of X belonging to H_0, and γ is the threshold which is obtained from Eq. (6.6):

$$P_{FA} = \int_{\{x:L(x)>\gamma\}} p\left(x;\, H_0\right) dx = \alpha \tag{6.6}$$

The test statistic and the threshold were calculated by simplification of Eqs. (6.5) and (6.6), respectively, and are shown in Eqs. (6.7) and (6.8):

$$T_{mk}(X) = \sum_{i=1}^{N-1} \frac{x_i\left(s_i' - s_i\right)}{\sigma^2} \tag{6.7}$$

$$\gamma_{lk}' = \frac{Q^{-1}\left(P_{FA}\right) * \mathrm{var}\left(T_{mk}\left(X\right)\right)}{\left(E\left(T_{mk}(X)\right)\right)} \tag{6.8}$$

where

x_i is the ith measurement for testing the hypothesis at segment m and time step k.

s_i' is the expected value of ith measurement under the incident case.

s_i is the expected value of ith measurement under the no-incident case.

$T_{mk}(X)$ is the test statistic to be compared with γ_{mk}'. If $T_{mk}(X) > \gamma_{mk}'$ we accept H_1 and conclude that there is an incident in Milepost m and time step k.

Results

The incident detection results for different scenarios are shown in Tables 6.2 and 6.3. Table 6.2 shows the results for Method I with different test segment resolutions. As shown in Table 6.2, this method was unable to detect the incidents when the network was congested when the incident detection threshold was set to 95% and 99% of the average normal acceleration distribution. When the threshold was changed to 99%, the PFA and DR decreased as expected but the method could not detect incidents after the merge even under no-breakdown conditions The reason appears to be the

Table 6.2 Method I incident detection results

				Incident before merge			Incident after merge		
H.R[a]	T[b]	Congestion level	MP (%)	DR %	PFA%	MTTD	DR %	PFA%	MTTD
30 ft.	95%	With breakdown	3	Unable to detect			Unable to detect		
			20						
		Without breakdown	3	100%	4.5%	1 min	100%	2.43%	1 min
			20	100%	3.65%	1 min	100%	1.57%	1 min
	99%	With breakdown	3	Unable to detect			Unable to detect		
			20						
		Without breakdown	3	85%	0.48%	2 min	Unable to detect		
			20	85%	0.32%	2 min			
60 ft.	95%	With breakdown	3	Unable to detect			Unable to detect		
			20						
		Without breakdown	3	100%	2.81%	1 min	100%	1.16%	1 min
			20	100%	2.57%	1 min	100%	1.08%	1 min
	99%	With breakdown	3	Unable to detect			Unable to detect		
			20						
		Without breakdown	3	70%	0	2 min	Unable to detect		
			20	75%	0	2 min			
90 ft.	95%	With breakdown	3	Unable to detect			Unable to detect		
			20						
		Without breakdown	3	100%	2.67%	1 min	100%	0.79%	1 min
			20	100%	2.48%	1 min	100%	0.42%	1 min
	99%	With breakdown	3	Unable to detect			Unable to detect		
			20						
		Without breakdown	3	Unable to detect			Unable to detect		
			20	70%	0	2 min			

[a]Hypothesis testing resolution
[b]Threshold

Table 6.3 Method II incident detection results

		Incident before merge			Incident after merge		
Congestion level	MP (%)	DR %	PFA%	MTTD	DR %	PFA%	MTTD
With breakdown	3	100	0	1 min	100	0.02	1 min
	20	100	0	1 min	100	0	1 min
Without breakdown	3	100	0.2	1 min	100	0.46	1 min
	20	100	0.06	1 min	100	0.3	1 min

overlap between the average acceleration distribution beyond the incident location and the average acceleration distribution beyond the on-ramp merge location, which make the differentiation between these two conditions difficult. As can be seen from Table 6.3, 90 ft. testing segment resolution produced the best incident detection performance, but it was still not able to detect incidents at the merge area during traffic breakdown. Table 6.3 shows that Method II (the LTR method) performed significantly better than Method I, particularly for breakdown conditions, in terms of the ability to detect the incidents and false alarm rates. The probability of false alarm was set to 10^{-4} (threshold: 9999th percentile) and with this probability of false alarm it was possible to obtain the best performance of incident detection among the methods and parameters tested, as shown in Table 6.3. Compare to the other probe-based methods reviewed in the literature, Method II demonstrated promising performance with the average DR of 100%, FAR of 0.13%, and MTTD of 1 min.

Queue Warning

In the previous section, the incident detection method based on CV data, as utilized in this study, was explained. Once the incident is detected, the back-of-queue estimation algorithm and queue warning are activated in the simulation model. To identify the back of queue, the segments are sorted based on their position, compared to the incident location. If a segment average speed is below a threshold, the segment is considered queued. The algorithm continues to test if the next upstream segment is queued and the first unqueued segment upstream of the incident is declared as the back of queue. The BOQ estimation algorithm is shown in Fig. 6.1. Lastly, the performance of the connected vehicle-based BOQ detection is compared with the ground truth queue based on VISSIM results and with the queue estimated based on point detection in the simulation. The point detector-based BOQ algorithm is taken from the Pesti et al. [28] study, which estimates the location of queue using the following equation:

$$X = X_{\mathrm{DET}}(i) + \frac{1}{2}\Delta X_{\mathrm{DET}} \tag{6.9}$$

where

X = back-of-queue location.

$X_{\mathrm{DET}}(i)$ = distance from the incident location to the speed detector i.

ΔX_{DET} = detector spacing.

The queue warning system is activated when the incident (or recurrent bottleneck) is detected and the queue starts growing. In this study, the queue warning impact is modeled by changing a certain percentage of a vehicle's speed upstream of the queue using the VISSIM COM interface. It is assumed that the back of queue is detected by the connected vehicle data and the queue warning message is shown dynamically at a specific location upstream of the back of queue using a DMS or connected vehicle onboard units (OBUs). The proportions of vehicles changing speeds in response to OBU messages reflect the number of connected vehicles equipped with OBU and driver acceptance of the message advisory. In the future, with the introduction of connected automated vehicles, the response to queue warning messages will be set automatically by the vehicle, and the driver acceptance will become less of a factor.

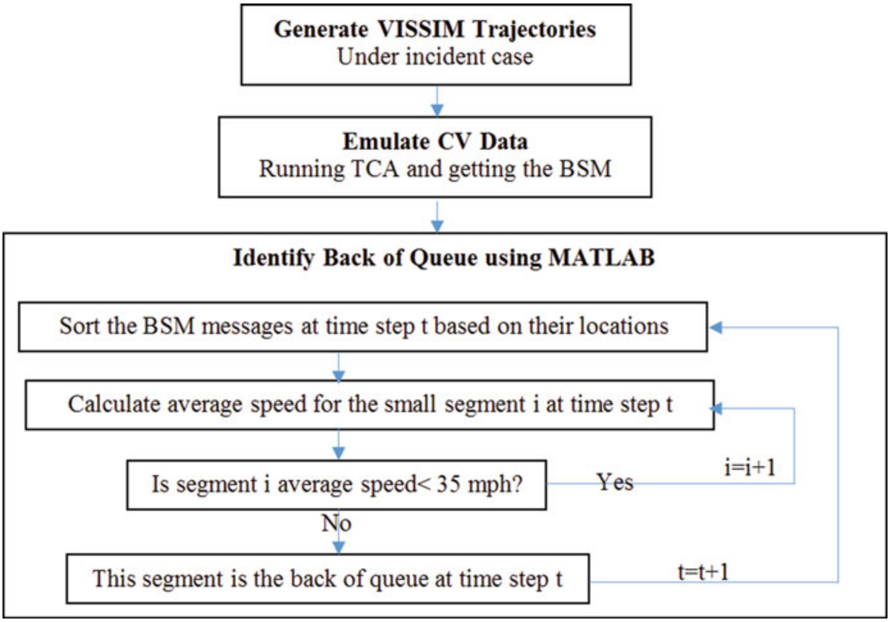

Fig. 6.1 Back-of-queue (BOQ) estimation algorithm

The vehicle's trajectories produced by VISSIM are fed to the TCA tool to emulate BSM messages generating from the simulated vehicles. The generated BSM messages are input to the incident and BOQ detection algorithms utilized in this study to investigate their performances. The results of this part can be found in Reference [29].

References

1. Cho, H.-J., & Hwang, M.-C. (2005). Day-to-day vehicular flow dynamics in intelligent transportation network. *Mathematical and Computer Modelling, 41*(4–5), 501–522.
2. Zhou, B., Cao, J., Zeng, X., & Wu, H. (2010). Adaptive traffic light control in wireless sensor network-based intelligent transportation system. In *IEEE 72nd Vehicular Technology Conference Fall (VTC 2010-Fall)*.
3. Amini, M. H., & Karabasoglu, O. (2018). Optimal operation of interdependent power systems and electrified transportation networks. *Energies,* 11(1):1–25.
4. Adeli, H., & Jiang, X. (2008). *Intelligent infrastructure: neural networks, wavelets, and chaos theory for intelligent transportation systems and smart structures* (Vol. 154, pp. 245–256). Boca Raton: CRC Press.
5. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks*. Berlin: Springer.
6. Amini, M. H., Kargarian, A., & Karabasoglu, O. (2016). ARIMA-based decoupled time series forecasting of electric vehicle charging demand for stochastic power system operation. *Electric Power Systems Research, 140*, 378–390.

7. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). A panorama of future interdependent networks: from intelligent infrastructures to smart cities. In *Sustainable interdependent networks*. Berlin: Springer.
8. Parkany, E., & Xie, C. (2005). *A complete review of incident detection algorithms & their deployment: what work and what doesn't*. Amherst, MA: The New England Transportation Consortium.
9. Mahmassani, H. S., Hass, C., Zhou, S., & Peterman, J. (1999). *Evaluation of incident detection methologies*. Center for Transportation Research, The University of Texas at Austin, Austin, TX.
10. Wu, W., Wang, H., & Alluri, P. (2013). *Automatic incident detection using real-time traffic detector data*. Department of Civil and Environmental Engineering, Florida International University, Miami, FL.
11. Chue, R., Qi, H., & Lee, D. (2002). Mobile sensor and sample-based algorithm for freeway incident detection. *Transportation Research Record, 1811*, 12–20.
12. Stephanedes, Y. J., Chassiakos, A. P., & Michalopoulos, P. G. (1992). Comparative performance evaluation of incident detection algorithms. *Transportation Research Record, 1360*, 50–57.
13. Mahmassani, H. S., & Hass, C. (1998). *Evaluation of incident detection methodologies.* Austin, TX: Center for Transportation Research, University of Texas at Austin.
14. Petty, K. F., Skabardonis, A., & Varaiya, P. P. (1997). Incident detection with probe vehicles: performance, infrastructure requirements and feasibility. *Transportation Systems: A Proceedings Volume from the 8th IFAC/IFIP/IFORS Symposium* (vol. 1, pp. 125–130).
15. Mohammadi, A., & Dehghani, M. J. (2014). Spectrum allocation using fuzzy logic with optimal power in wireless network. In *2014 4th International eConference on Computer and Knowledge Engineering (ICCKE)* (pp. 532–536).
16. Martin, P., Perrin, J., Hansen, B., Kump, R., & Moore, D. (2009). *Incident detection algorithm evaluation*. Utah Department of Transportation, Taylorsville, UT.
17. Stephanedes, Y., Chassiakos, J., & Athanasios, P. (1991). Low pass filter for incident detection. In *2nd International Conference on Applications of Advanced Technologies in Transportation Engineering*, ASCE.
18. Cook, A. R. (1974). Management of urban freeway traffic. *Canadian Journal of Civil Engineering, 1*(2), 141–149.
19. Levin, M., & Krause, G. (1979). Incident-detection algorithms, Part 1. Off-line evaluation. *Transportation Research Record, 722*, 49–64.
20. Parkany, E., & Bernstein, D. (1995). Design of incident detection algorithms using vehicle-to roadside communication sensors. *Transportation Research Record, 1494*, 67–74.
21. Balke, K., Dudek, C., & Mountain, C. (1996). Using probe-measured travel time to detect major freeway incidents in Houston, Texas. *Transportation Research Record, 1554*, 213–220.
22. Mouskos, K. C., Niver, E., Pignataro, L., Lee, S., Antoniou, N., & Papadopoulos, L. (1998). *Evaluation of the TRANSMIT system*. Newark, NJ: Institute for Transportation, New Jersey Institute of Technology.
23. Hellinga, B., & Knapp, G. (2000). Automatic vehicle identification technology-based freeway incident detection. *Transportation Research Record, 1727*, 142–153.
24. Crabtree, J., & Stamatiadis, N. (2007). Dedicated short-range communications technology for freeway incident detection. *Transportation Research Record, 2000*, 59–69.
25. Yu, W., Park, S., Kim, D., & Ko, S. (2015). Arterial road incident detection based on time-moving average method in bluetooth-based wireless vehicle reidentification system. *Journal of Transportation Engineering, 141*, 3, 401–408.
26. Asakura, Y., Kusakabe, T., Xuan Long, N., & Ushiki, T. (2015). Incident detection methods using probe vehicles with on-board GPS equipment. *Transportation Reaserach Procedia, 6*, 17–27.
27. Kay, S. (1998). *Fundamentals of statistical signal processing volume II: Detection theory*. Upper Saddle River: Prentice-Hall PTR.

28. Pesti, G., Chu, C.-L., Charara, H., Ullman, G., & Balke, K. (2013). Simulation based evaluation of dynamic queue warning system performance. *Transportation Research Record: Journal of the Transportation Research Board*, 1–16.
29. Khazraeian, S., Hadi, M., & Xiao, Y. (2017). Safety impacts of queue warning in a connected vehicle environment. *Transportation Research Record: Journal of the Transportation Research Board, 2621*, 31–37.

Chapter 7
Sustainable Interdependent Networks from Smart Autonomous Vehicle to Intelligent Transportation Networks

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Introduction: Autonomous Vehicle

Over the last century, the invention of cars and other type of vehicles has immensely benefitted people in large [1]. Whether for personal transportation, or for moving goods and services, vehicles connect people to one another as well as connect people to the goods and services they need [2]. As technology improves, vehicles have become ever-increasingly efficient, and easily accessible to the common people, and they can be operated relatively easy and safe [3]. As of more recent update in technology, much focus has been targeted at developing machine intelligence, so-called artificial intelligence (AI), which could develop their own intelligence through self-learning method, thus decreasing the dependence of these machines on decision input by human. Instead, the machines develop their own behavior and subsequent actions based on their own intelligence and perception dictated by information obtained by the machines [4].

The development of artificial intelligence has not overlooked the vehicle sector; in fact, artificial intelligence in vehicle is one of the forefronts in the groundbreaking research that has garnered attention by the many. Household car manufacturers and technological start-ups are vying to be the first to introduce fully autonomous cars to the public consumers, with some pundits believing that the technology would be readily available and fully transitioned into the market come 2030 [1, 5, 6]. It is important to note that the autonomous driving technology has been infused into the market although at varying level but not fully autonomous which is still very much

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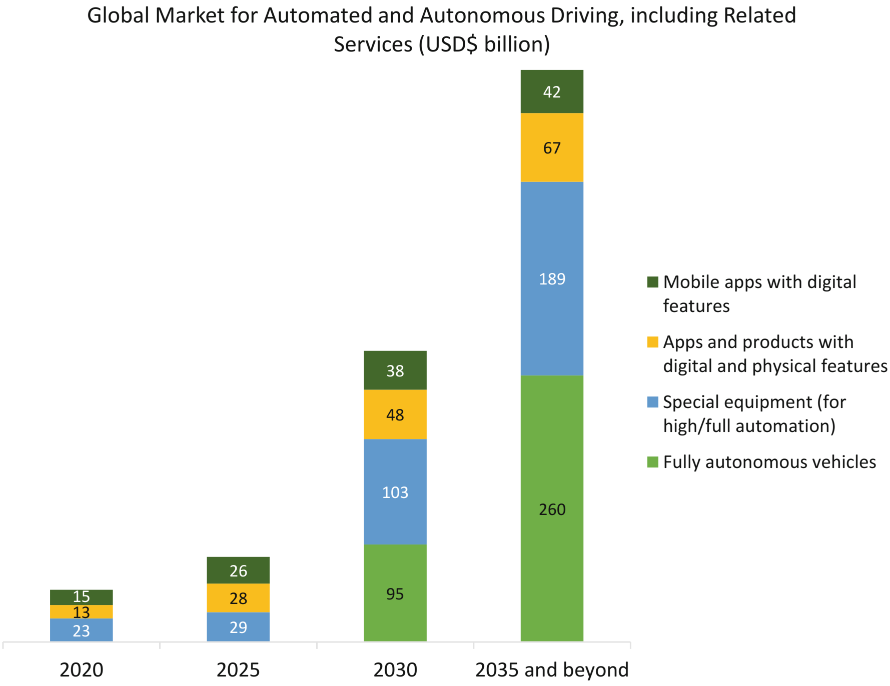

Fig. 7.1 Prospective global market for autonomous related products and services [8]

under development [7]. In 2014, SAE International has developed the indicator for the level of autonomous driving from no automation (level 0) to full automation (level 5) (Fig. 7.1). Full automation is defined as “the full-time performance by an automated driving system of all aspects of the dynamic driving task under all roadway and environmental conditions that can be managed by a human driver.” Levels 1–3 rely on having a driver, though at different level of intervention from a human driver during the operation, while levels 4 and 5 enable driverless operation of the vehicle (Table 7.1).

The idea of autonomous driving is expanded from the current assistance features installed in a vehicle to ease the driving experience, known as advanced driver-assistance systems (ADAS) which include adaptive cruise control, emergency braking, and other assistances including parking sensors, and self-parking systems. Over the past years, car manufacturers have been working on installing a driving assistant, parking control, and even fully autonomous systems to vehicles [2]. Numerous manufacturers, such as Google, Tesla, BMW, Toyota, and Volkswagen, have invested considerably in pilot studies around the world. Striking news came while stakeholders in the industry were working on a vigorous transformation of the mobility of people [7]. Companies such as nuTonomy and Uber took the lead in launching a driverless taxi service to the public in Singapore and Pittsburgh, and it could be confidently predicted that the service will spread to

Table 7.1 The level of automation (SAE International, 2014)

SAE level	Name	Definition	Steering control, acceleration/deceleration	Driving environment monitor	Fallback performance of dynamic driving task	System capability
0	Zero automation	Full-time performance expected from human driver, regardless of assistance by intervention/warning systems	Human driver	Human driver	Human driver	n/a
1	Driver assistance	Full-time performance expected from human driver, except **either** steering or acceleration/deceleration tasks, which are done by the system using information about the driving environment	Human driver and system	Human driver	Human driver	Some driving modes
2	Partial automation	Full-time performance expected from human driver, except for **both** steering and acceleration/deceleration tasks, which are done by the system using information about the driving environment	System	Human driver	Human driver	Some driving modes
3	Conditional automation	Specific performance by automated driving system on every aspects of driving, the human driver **is expected** to intervene upon request	System	System	Human driver	Some driving modes
4	High automation	Specific performance by automated driving system on every aspects of driving, the human driver **is not expected** to intervene even upon request	System	System	System	Some driving modes
5	Full automation	Full-time performance of automated system for **all** driving tasks	System	System	System	All driving modes

the wider public in the foreseeable future after experiments and evaluations have been finalized. In addition, the announcements from Ford, Toyota, and Apple about autonomous technology all indicate that we are encountering a dramatic change in the development of vehicles and systems [9].

For the autonomous cars, features such as smart software, endpoint telemetry, and cloud storage are essential enablers [10]. The onboard mounted sensors and cameras on an autonomous vehicle obtain huge amount of data in a short amount of time. The data is then simultaneously processed to ensure that the vehicle is safe in the proper lane until it reaches the intended endpoint [11]. In other words, a huge sum of local data processing is happening as it comes in, from detecting objects and environments to decision-making process and lastly the actual control on the car's navigation [12]. Concurrently, there are other processing tasks occurring in the background, namely updates on the vehicle software and upgrades for the learning model of the vehicle. A highly resilient cloud-based infrastructure of proper scale is of utmost importance for the system in order to handle the large-scale data processing in a speedy manner. In the meantime, cloud-based data management system and intelligent agents assume the task of accumulating and analyzing the real-time telemetric data—for instance, the proximity and position of the vehicle to the surrounding vehicles and potential blockade, and the vehicle speed. These data are then used to trigger subsequent actions like braking, turning at intersections, or changing lanes. Onboard systems of the autonomous vehicle allow for machine-to-machine communications, supporting the learning process of autonomous vehicles on the road in such a way that enables adjustments to be made factoring in for surrounding conditions such as shifting road conditions (e.g., detours and in-path debris) and weather changes. All these smart applications are driven by advanced algorithms, artificial intelligence, and deep machine learning systems enabling autonomous cars to seamlessly adapt to changing scenarios as quick as possible without having to resort to human intervention.

The market share of autonomous vehicle is expected to grow exponentially in the next 20–30 years. This can be envisaged as the technology matures and increasingly gets accepted among the mass consumers. The growth pace will be slower initially as improvements are made to the technology and the supporting infrastructure needs to be built to accommodate for the changes. Government incentives are expected to further accelerate the integration of autonomous vehicles into the consumer market. In the year 2030, it is expected that the market share of autonomous vehicles will be at 7% of the total automotive market. In 2035, the percentage is set to increase to 17% of the total automotive market.

Advantages of Autonomous Technology in Cars

Driverless cars or AVs were addressed in extensive discussions led by scholars, vehicle corporations, governments, and even the public with the essence being the potential of transforming the mode of transport by addressing it to the stage of the development of our transport mobility [13]. The prospect of having autonomous vehicles is welcomed by many researchers for many reasons. One of them is the prediction that the technology is projected to dramatically decrease the occurrence of vehicle collision and fatal crash. Based on the data, almost 33% of collisions especially involving fatalities are avoidable given that all vehicles are equipped with warning system for potential dangers like forward-collision warning, blind-spot assist on side view, and lane-departure warning [5, 14]. Advanced-level automation is thus projected to reduce more fatalities and save more lives; for example, automatic braking in the presence of an imminent obstacle will lower rear-end collisions, and fully autonomous cars will dramatically lower the human error-related accidents.

Autonomous vehicles are expected to advance mobility for groups who are physically and mentally challenged to operate vehicles, for example, young children, elderly people, and individuals with disability. The potential benefits would be increasing their social interaction, job opportunities, access to healthcare, and many others. Autonomous vehicles are the solution to providing independence and increased mobility for nondrivers; for some reason they are not able or should not be able to drive conventional vehicles [12]. This can provide direct benefits to those groups and reduce the dependence on individuals immediate to them, who would be able to attend to their own needs. Simultaneously, as scholars have demonstrated in relevant studies, a system that considers older people and children, its capacity increasing and well coordinated, will be generated by pushing forward the autonomous technology to reform the mode of transportation [15].

Meanwhile, the cost of traffic congestion to the drivers can be reduced with autonomous vehicle. Instead of spending a lot of time driving to reach their intended destination, the drivers are passengers in autonomous car, and they could utilize the time for other activities [12]. The technology is supposed to increase the amount of traffic on the roads largely to more efficient vehicle operation and lessened delays in excessive braking [16] making future traffic to be heavier. Nevertheless, the tedious and stressful act of driving is expected to be greatly reduced with the use of autonomous vehicles. Autonomous cars are converted into mobile rooms for activities such as offices, bedrooms, and playrooms, giving passengers increased time to spend on productive activities or simply get the rest on the road [17].

Over the years, automobiles have become heavier, partly in bid to surpass the more stringent crash-test standards. With the prospect of collisions and crashes lessening with autonomous vehicles, there might be a shift to producing lighter automobiles which are of greater fuel efficiency [16]. Another important feature of autonomous vehicle is that it can alight and drop off passengers at their desired destinations and then drive away to their designated parking areas [18]. This helps to reduce the need to allocate parking space, which is vital especially in urban centers where space is very valuable and vehicle parking is consuming a lot of space. Further, people are expected to shift from thinking about owning a car to using ride-sharing services as driverless cars reduce the need to own them. For instance, using the ride-sharing services will be easier as it solves parking issues, maintenance, and repair issues from the point of view of the consumers. In both cases, fewer parking spaces and reduced car ownership would be necessary (by one estimate, about 31% of the space in the central business districts was devoted to parking) and more space would be available for improving the built environment [13].

Disadvantages of Autonomous Technology in Cars

In the meantime, there is still a long way to be done to ensure that the technology is safe and reliable for mass use. For that, the potential downsides of the technology still need to be addressed [19–22]: some major ones including potential hardware and software failures. Complex electronic systems are susceptible to performance failures. Unlike failures in other machines, a minor vehicle operating system failure, such as a nonfunctioning signal, or software glitches can lead to calamitous and fatal accidents [17]. Autonomous vehicles, while equipped with advanced systems, are certainly fated to experience failures that might contribute to crashes, the exact problem which is supposed to correct from human driver error. Even more so, the source of failure can happen remotely via malicious hacking. Self-driving technologies are vulnerable to manipulation from the established communication networks in which the technology can be manipulated for crime or even amusement.

Another potential issue is increased risk-taking due to perceived safe condition of the technology among the car passengers as well as other road users [23]. This behavior is known as moral hazard, commonly known in economics, also known as risk compensation. Because of the perceived safe, the road users tend to take additional risks. The introduction of autonomous vehicles is exactly to be regarded to provide a very safe traveling experience; thus passengers may be prone to taking more risks and neglect basic safety rules such as seatbelt rule while pedestrians may become careless [24] while crossing roads for instance. Not only that, other benefits such as reduced congestion require the vehicles to operate at high speeds while moving close to each other. This will lead to new risks detrimental to the road users, such as having human drivers on the road driving at high speeds. As a result, this can increase the chance of crashes occurring as well as increase their severity. This is only made worsen with the projection that the number of vehicles on the road is expected to increase due to the improved convenience and comfort of autonomous vehicle, hence heightening the level of risks aforementioned [25, 26].

In the end, many factors will affect these safety impacts, including how vehicles are programmed, and the projections of net total vehicle travel with the introduction of autonomous vehicle, whether it increases or otherwise. This projection is crucial as it determines what is at stake. For instance, maximizing mobility might require autonomous vehicles to be programmed to move at higher speed, take increased risks in precarious situations, etc. Or in another instance, maximizing safety means the vehicles are programed to drive slower, take less risk, etc. This depends hugely on how the technology is developed to incorporate the risks associated to autonomous driving and decision-making process of the machine. And for this, ethical consideration is pertinent to the process to ensure accountability of the producers to the consumers.

Review of Past Research

By reviewing studies among previous research on autonomous cars, inferences and gaps could be extracted. The research on autonomous revealed the connections between these two subjects, in particular toward the implication of the technology and users' features. Howard and Dai [27] illustrated the preference of the technology changing the variables offered by autonomous cars, whereas Payre et al. addressed more factors with regard to the theoretical acceptability of the transport mode, which represented the participants' interests well [28]. Furthermore, the correlation between the acceptance of individuals at the national level was discussed when revealing the interaction between people's concerns and the nation's concerns in terms of development and education [29]. In 2016, Hohenberger et al. went deeper by explaining the effect of gender on the respondents' usage of autonomous cars [30]. Paper studied by Hulse et al. looks at the consumers' perceptions by classifying into several demographic categories (age, gender, etc.) [31]. As such, for studies in the future, the expansion of the factors, multiple perspectives when selecting the respondents, and scenarios that establish the autonomous car technology under different operation conditions should be focused (e.g., shared autonomous vehicles). Following that, more valuable variables contained in the effect of the respondents' attitudes could be considered, which could remove the potential barriers that restricted the prior assessments. Other possible aspects that could be taken into consideration are the consumers' willingness to pay for different levels of automation in terms of people's features [32, 33]; consideration of the supply- and demand-side factors when viewing the annual drops in technology prices and increments in willingness to pay [18]; and potential benefits, concerns, and implications based on the users' viewpoints [34]. Another important aspect that should be in line for future research is the ethical implications of the autonomous technology [35].

Ethical Implication of Autonomous Technology

Future direction of human mobility and transportation is looking increasingly toward autonomous technology. As such, there is a greater need to prepare policy guidelines as the foundation to set up the systems as such to keep on being human centric rather than machine centric, ultimately to serve based on humanity's values and ethical principles [23]. In other words, the built systems have to perform in such a way as to benefit people, especially the masses and those who are at disadvantage in the current system, which is beyond solving technical problems and meeting the functional objectives [1]. What is needed especially at the critical point of breaking the technological acceptance barrier is to establish a sense of trust between people and the new technology which is greatly needed as machines are increasingly integrated into our lives. There are several ethical considerations that should be put into focus by the manufacturers and policymakers based on several aspects:

Personal Data Rights and Access to Control

This is one of the most important aspects of living in the Fourth Industrial Revolution, whereby the amount of data shared by an individual is exorbitant encompassing the lifestyle as a whole. As in any other technological application, autonomous systems need to accommodate the fundamental right of the consumers to define their own liking, access to their personal data, and make available information on how their personal digital data are used [16]. Having control of options on what to be shared is needed for individuals to give consent to their personal data being used in the systems, making them consensually aware of the consequences of sharing the personal information [11].

Transparency and Individual Rights

The automation of decision-making process in autonomous technology is largely due to the self-improving and learning algorithms and data analytics, and these are built by the technology makers with the guidance of governments and other legal authorities [36]. As such, the systems employed have certain rules and logic applied to them, embedded within the systems. These logic and rules should be made transparent and available by the authorities for outside expert scrutiny and risk evaluation and rigorous testing [37]. It is within the rights of the public to have reasonable access to all the information and data gathered and generated by the system especially when it involves ethical and legal issues [36]. The systems must then produce audit trails gathering the facts and legalities supporting verdicts in any dispute, and they are ought to be subject to third-party verification [38]. The general public are ought to be informed of the individuals behind the scene, making or supporting ethical decisions of such systems through investment [39]. All these are a part of the legal requirements mandating transparency and accuracy of the systems.

Education and Awareness Policies

Education is the key to ensuring successful integration of autonomous vehicles into the mass market. Education and awareness policies must confront the issue of maintaining and promoting of cybersecurity, safety, intellectual property rights, privacy, and last but not least understanding of the potential effect of autonomous systems on society at large [11]. The policies should be designed in such a way that serves the public interest and promotes the advancement of the less fortunate members of the society. Therefore, emphasis should be taken to ensure that the less fortunate group is receiving the information and awareness despite their disadvantages, especially on how they can benefit from the technology. Another important thing to put in mind of the policymakers is to ensure proper standardization of the policies to be implemented and that they are internationally recognized and accepted [40]. As much as technological advancement is concerned, priority should also be given in promoting further advance in technologies as well as attaining highly skilled human capital to develop expertise in the field.

Legal Frameworks for Accountability

The emergence of artificial intelligence technology is attributed to the building of control systems with traits mimicking those of human characteristics in terms of partial autonomy, the ability to undergo decision-making process and later use it to accomplish specific tasks with intellectual value, and may even have a human physical appearance [38]. The issue of the legal status of complex intelligent and autonomous technical systems thus intertwines with broader legal questions regarding how to ensure accountability and allocate liability when such systems cause harm. Some examples of general frameworks to consider include the following: intelligent and autonomous technical systems should be subject to the applicable regimes of property law [39]. Government and industry stakeholders should identify the types of decisions and operations that should never be delegated to such systems and adopt rules and standards that ensure effective human control over those decisions and how to allocate legal responsibility for harm caused by them [41].

Economic Effects of Open Access to Autonomous Systems

Through affordable and universal access to the Internet and other communications networks, autonomous technical systems can be designed to be accessible to populations regardless of the location [2]. The systems can potentially shape establishments and institutional relationships to lean for greater human-centric structures. As a result, the technology serves the purpose of advancing development and humanitarian issues which potentially brings benefits such as elevated societal well-being and greater individual independence and mobility [7].

Autonomous Cars in the Future Smart Cities

As the prospect of autonomous cars lining up and dashing on the roads is more inevitable than ever, it is important for cities, especially future smart cities, to carefully plan about integrating them into the larger urban planning system. The planning should always have the potential advantages and disadvantages of the technology in mind; thus it will be easier to maximize the potential while mitigating the adverse impacts of autonomous vehicles. One important goal to be achieved by the introduction of the autonomous vehicles is to create a more socially mobile transportation system, especially for the people who are at disadvantage in the current system (e.g., physically challenged individuals, elderly people, and people who are afraid to drive). In other words, cities should plan a transportation that is accessible to everyone especially people with special needs. This could be achieved by building supporting infrastructure, making the system at minimal cost, and allowing individuals from low-income societies to benefit too [42]. In other words, the cities should look at increasing the acceptance rate of the technology so that it is not going to be benefitted by the early adopters only [10, 43]. Not only that, future smart cities should be equipped with the state-of-the-art communication technology. This is to accommodate the influx of information flow, be it machine-to-machine communication or machine-to-infrastructure communication. All these need to be done within a fraction of second for the data processing for instantaneous decision-making process. Hence, a wireless communication channel that is capable of handling this huge amount of data is needed in the future smart cities [44]. Another big idea that should be considered by cities is to introduce shared autonomous transportation system [44]. This is important since the autonomous technology is expected to increase the number of cars on the road. Hence, having a shared system will be effective at optimizing the road space for traveling while reducing traffic congestion. In the end, autonomous vehicle will change our perspective on sustainability in the form of mobility and accessibility, as illustrated above. Interdependent networks, comprising large-scale complex networks ranging from energy, communications, and transportation, are enablers for such system to operate, benefitting the population as a whole (Fig. 7.2).

Conclusion and Discussion

In the future, more research is needed especially to close the gap in ethical considerations within autonomous technology. Laws and regulations are ought to be reviewed and amended to allow autonomous cars to start being on the road and the process is not simply to transfer the rights to handle vehicle from individuals to machine [41, 45]. Rather, we should be more specific about shaping how the machine can operate in such a way that conforms with the ethics that we are upholding [16]. The ethical issue definitely is a lengthy discussion up for a debate. Consider one scenario: If the autonomous cars are designed to choose on avoiding collision based on the number of potential casualties, would people be incentivized to travel in public transportation and avoid autonomous vehicle? How about the safety of single-user transportation such as bicycle? Logically this will increase the likelihood of surviving in the event a collision would occur with involving

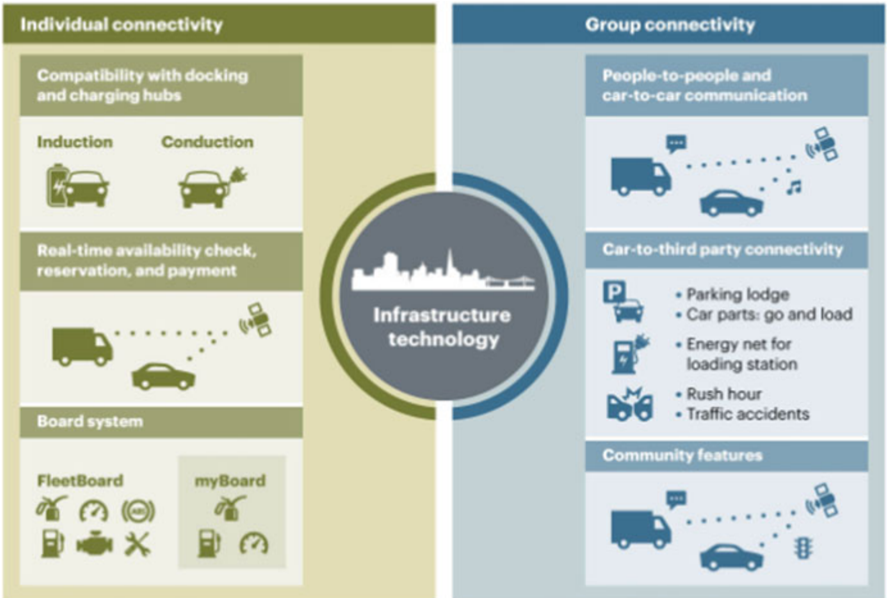

Fig. 7.2 Rinspeed's concept on interdependent network system [8]

various types of vehicles. In the meantime, it is telling to suggest an autonomous car decide the number of casualties that could be saved in an imminent collision with a larger passenger vehicle, even when the larger vehicle is empty and the car is full with people. This utilitarian approach, that is, decisions based on casualty numbers, seems to be logically far-fetched and unfair to many road users who travel in smaller vehicles. This is counterintuitive and works in the opposite of government campaigns to promote walking and cycling as a healthier and cleaner transportation mode.

The advancement in technology should always be more humane centric, putting into consideration of ethical aspects, especially safety, accountability, economic prosperity, and individual rights. The underlying issue is the limitation on our behalf; it is beyond our knowledge of how autonomous car in future should be like. As it applies here, artificial intelligence is not merely taking the place of human drivers, so much so human drivers in the first automobiles were not like-to-like replacement for horses in horse carriage. The technology enables for more functions and operations which can be beyond what we can envisage today. The potential shakeup of automating transportation will shift the society in radical ways, while technology seems to show no signs of slowing down. When technology goes wrong, and there is no doubt that it will inevitably happen, some forward thinking about the ethical design and policies can help steer the development of technology toward which brings the most benefit to all of us.

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References

1. Nagler, J., van den Hoven, J., & Helbing, D. (2018). *Ethics for times of crisis: How; not to use autonomous systems in an unsustainable world*.
2. Fagnant, D. J., & Kockelman, K. M. (2014). The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies, 40*, 1–13.
3. Fleetwood, J. (2017). Public health, ethics, and autonomous vehicles. *American Journal of Public Health, 107*(4), 532–537.
4. Litman, T. (2017). *Autonomous vehicle implementation predictions*. Victoria: Victoria Transport Policy Institute.
5. Gao, P., Kaas, H.-W., Mohr, D., & Wee, D. (2016). *Automotive revolution–perspective towards 2030: How the convergence of disruptive technology-driven trends could transform the auto industry*. New York: Advanced Industries, McKinsey.
6. K. Heineke, P. Kampshoff, Mkrtchyan, A., & Shao, E. (2017). *Self-driving car technology: When will the robots hit the road?* McKinsey Global Institute. www.mckinsey.com/industries/automotive-and-assembly/our-insights/self-driving-car-technology-when-will-the-robots-hit-the-road.
7. Gogoll, J., & Müller, J. F. (2017). Autonomous cars: In favor of a mandatory ethics setting. *Science and Engineering Ethics, 23*(3), 681–700.
8. Kearney, A. T. (2016). *How automakers can survive the self-driving era*. Retrieved November (vol. 14, p. 2017).
9. Reese, H. (2016, January 20). *Autonomous driving levels 0 to 5: Understanding the differences*, TechRepublic.
10. Adnan, N., Nordin, S. M., Rahman, I., & Amini, M. H. (2017). A market modeling review study on predicting Malaysian consumer behavior towards widespread adoption of PHEV/EV. *Environmental Science and Pollution Research, 24*(22), 17955–17975.
11. Adnan, N., Nordin, S. M., & Althawadi, O. M. (2018). Barriers towards widespread adoption of V2G technology in smart grid environment: from laboratories to commercialization. In *Sustainable interdependent networks* (pp. 121–134). Berlin: Springer.
12. Zhao, W., Gong, M., Chen, Y., Jiang, B., & Chen, H. (2017). Research on navigation method of substation inspection car based on image recognition. In *Chinese Automation Congress (CAC), 2017*, (pp. 3236–3240).
13. Anderson, J. M., Nidhi, K., Stanley, K. D., Sorensen, P., Samaras, C., & Oluwatola, O. A. (2014). *Autonomous vehicle technology: A guide for policymakers*. Santa Monica, CA: Rand Corporation.
14. Fagnant, D., & Kockelman, K. M. (2015). *Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transportation Research Part A, 77*, 167–181.
15. Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice, 77*, 167–181.
16. I. S. Association. (2017). *The IEEE global initiative on ethics of autonomous and intelligent systems*. IEEE.org. [Online]. Retrieved from http://standards.ieee.org/develop/indconn /ec/autonomous_systems.html.

17. Anderson, J. M., Kalra, N., Stanley, K. D., Sorensen, P., Samaras, C., & Oluwatola, O. A. (2014). *Autonomous vehicle technology: How to best realize its social benefits*.," Brief. Santa Monica, CA: RAND Corporation.
18. Bansal, P., & Kockelman, K. M. (2017). Forecasting Americans' long-term adoption of connected and autonomous vehicle technologies. *Transportation Research Part A: Policy and Practice, 95*, 49–63.
19. Fagnant, D. J., & Kockelman, K. M. (2018). Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas. *Transportation, 45*(1), 143–158.
20. Koopman, P., & Wagner, M. (2017). Autonomous vehicle safety: An interdisciplinary challenge. *IEEE Intelligent Transportation Systems Magazine, 9*(1), 90–96.
21. Ohnsman, A. (2014, July). *Automated cars may boost fuel use, toyota scientist says*. Bloomberg (vol. 16).
22. Zhu, F., & Ukkusuri, S. V. (2015). A linear programming formulation for autonomous intersection control within a dynamic traffic assignment and connected vehicle environment. *Transportation Research Part C: Emerging Technologies, 55*, 363–378.
23. Bonnefon, J.-F., Shariff, A., & Rahwan, I. (2015). Autonomous vehicles need experimental ethics: Are we ready for utilitarian cars? *arXiv preprint arXiv:1510.03346*.
24. Millard-Ball, A. (2016). Pedestrians, autonomous vehicles, and cities. *Journal of Planning Education and Research, 36*(2), 210–224. https://doi.org/10.1177/0739456X16675674.
25. Trommer, S., Kolarova, V., Frädrich, E., Kröger, L., Kickhöfer, B., Kuhnimhof, T., et al. (2016). *Autonomous driving-the impact of vehicle automation on mobility behaviour*. Munich: Institute for Mobility Research (ifmo).
26. Kröger, L., Kuhnimhof, T., & Trommer, S. (2016). Modelling the impact of automated driving–private autonomous vehicle scenarios for Germany and the US. In *European Transport Conference 2016 Association for European Transport (AET)*.
27. Howard, D., & Dai, D. (2014). Public perceptions of self-driving cars: The case of Berkeley, California. In *Transportation Research Board 93rd Annual Meeting* (vol. 14, no. 4502).
28. Payre, W., Cestac, J., & Delhomme, P. (2014). Intention to use a fully automated car: Attitudes and a priori acceptability. *Transportation Research Part F: Traffic Psychology and Behaviour, 27*, 252–263.
29. Kyriakidis, M., Happee, R., & de Winter, J. C. F. (2015). Public opinion on automated driving: Results of an international questionnaire among 5000 respondents. *Transportation Research Part F: Traffic Psychology and Behaviour, 32*, 127–140.
30. Hohenberger, C., Spörrle, M., & Welpe, I. M. (2017). Not fearless, but self-enhanced: The effects of anxiety on the willingness to use autonomous cars depend on individual levels of self-enhancement. *Technological Forecasting and Social Change, 116*, 40–52.
31. Hulse, L. M., Xie, H., & Galea, E. R. (2018). Perceptions of autonomous vehicles: Relationships with road users, risk, gender and age. *Safety Science, 102*, 1–13.
32. Daziano, R. A., Sarrias, M., & Leard, B. (2017). Are consumers willing to pay to let cars drive for them? Analyzing response to autonomous vehicles. *Transportation Research Part C: Emerging Technologies, 78*, 150–164.
33. Schoettle, B., & Sivak, M. (2014). *A survey of public opinion about autonomous and self-driving vehicles in the US, the UK, and Australia*.
34. König, M., & Neumayr, L. (2017). Users' resistance towards radical innovations: The case of the self-driving car. *Transportation Research Part F: Traffic Psychology and Behaviour, 44*, 42–52.
35. Goodall, N. J. (2014). Machine ethics and automated vehicles. In *Road vehicle automation* (pp. 93–102). Berlin: Springer.
36. Arkin, R. C. (2016). Ethics and autonomous systems: Perils and promises [point of view]. *Proceedings of the IEEE, 104*(10), 1779–1781.
37. Hevelke, A., & Nida-Rümelin, J. (2015). Responsibility for crashes of autonomous vehicles: An ethical analysis. *Science and Engineering Ethics, 21*(3), 619–630.
38. Millar, J. (2017). 2 ethics settings for autonomous vehicles. In *Robot ethics 2.0: From autonomous cars to artificial intelligence* (p. 2). Oxford: Oxford University Press.

39. Sparrow, R., & Howard, M. (2017). When human beings are like drunk robots: Driverless vehicles, ethics, and the future of transport. *Transportation Research Part C: Emerging Technologies, 80*, 206–215.
40. Lin, P., Bekey, G., & Abney, K. (2008). *Autonomous military robotics: Risk, ethics, and design*. San Luis Obispo: California Polytechnic State Univ.
41. Hashim, H. H., & Omar, M. Z. (2017). Towards autonomous vehicle implementation: Issues and opportunities. *Journal of the Society of Automotive Engineers Malaysia, 1*(2), 111–123.
42. Amini, M. H., Moghaddam, M. P., & Karabasoglu, O. (2017). Simultaneous allocation of electric vehicles' parking lots and distributed renewable resources in smart power distribution networks. *Sustainable Cities and Society, 28*, 332–342.
43. Sachan, S., Amini, M. H., & Adnan, N. (2018). Stochastic charging of electric vehicles in smart power distribution grids. In *Sustainable cities and society*. Berlin: Springer.
44. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Blaabjerg, F., Pardalos, P. M., & Madni, A. M. (2018). A panorama of future interdependent networks: from intelligent infrastructures to smart cities. In *Sustainable interdependent networks* (pp. 1–10). Berlin: Springer.
45. Lin, P. (2016). Why ethics matters for autonomous cars. In *Autonomous driving* (pp. 69–85). Berlin: Springer.

Chapter 8
TRAJEDI: Trajectory Dissimilarity

Kenrick Fernande, Pedram Gharani, and Vineet Raghu

Introduction

The vast increase in our ability to obtain and store trajectory data necessitates trajectory analytics techniques to extract useful information from this data. In fact, trajectory analysis is an essential function in intelligent transportation systems (ITS), and by applying it for the spatial trajectory data a wide range of transportation problems can be solved. Pair-wise distance functions are a foundation building block for common operations on trajectory datasets including constrained SELECT queries, k-nearest neighbors, and similarity and diversity algorithms. The accuracy and performance of these operations depend heavily on the speed and accuracy of the underlying trajectory distance function, which is in turn affected by trajectory calibration. Current methods either require calibrated data or perform calibration of the entire relevant dataset first, which is expensive and time consuming for large

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datasets. We present TRAJEDI, a calibration aware pair-wise distance calculation scheme that outperforms naive approaches while preserving accuracy. We also provide analyses of parameter tuning to trade-off between speed and accuracy. Our scheme is usable with any diversity, similarity, or k-nearest neighbor algorithm.

Ubiquitous mobile devices are able to collect various types of data especially motion-related ones such as location to estimate the similarity between users [32], inertial data for improving context-awareness [9, 19], or even visual data for micro-navigation [8]. In the past several decades, having location of vehicles using GPS sensors while moving has played an important role in improving transportation quality in smart cities using intelligent infrastructure [1], [2]. Proliferation of GPS-equipped mobile devices, advances in positioning technologies, and mobile computing have enabled researchers to collect trajectory data of people while moving through transportation network. Trajectory data is a series of time-stamped locations with a certain frequency from vehicles such as taxis and buses.

Spatial trajectory provides an invaluable dataset for solving wide range of transportation problems. Trajectory analysis is a necessary foundation in intelligent transportation systems (ITS) for dealing with challenges such as resource allocation [25, 27], traffic analysis [21, 25], improving transportation networks [33], traffic prediction [21], detect the problematic design in a city's transportation network [31], identify urban functional regions [28], evaluate trajectory classification and activity recognition [29],[30], evaluate trajectory pattern mining task [11], detecting community structure in a physical network using social network technique [12], and real-time tracking of vehicle through wireless networks. Competent wireless networks play an important role in communication among mobile sensors [14]. Mohammadi et al. proposed an energy-efficient spectrum allocation which considerably reduces the energy consumption of wireless networks using a novel fuzzy logic-based framework [14].

Spatial data has enjoyed increasing recognition for its uniqueness over the past few decades. Over the past decade in particular, the rise in location-enabled devices, smart or otherwise, has led to an increase in the spatial and trajectory data available. The corresponding rise in cheaply-available computational power and storage capacity has been exploited by spatial databases such as T-Drive [24, 26] and GeoLife [32]. These are however just the raw ingredients needed to extract information from the data. Trajectory data, our focus in this paper, can provide valuable insights in a variety of scenarios ranging from business advertising and recommendation [13] and geo-social media [3] to disaster planning [16] and green commuting route decision making [6, 17].

A variety of trajectory storage and analysis techniques have already been proposed in the literature to, for example trajectory pattern mining [11], unveiling the complexity of human mobility [10], trajectory search [7], semantic query of trajectory [4], and similarity search [5]. Distance measures for similarity/dissimilarity are a key building block for a variety of trajectory analysis algorithms, such as diversity [22] and k-nearest neighbors [23]. Currently, Dynamic Time Warping [20] and Synchronized Euclidean Distance [15] enjoy acceptance and popularity as distance measures for trajectories. However, a key real-world challenge often not addressed in this context is the variable sampling rate for available trajectory data. Since trajectory data comes from a variety of sources, simply cleaning data is insufficient for the preprocessing phase. To address this challenge, the literature contains work on calibration methods for trajectory data [18].

Calibration, while useful, is an expensive operation. Our experimental evaluations show that state-of-the-art grid based calibration, proposed in [18] has nearly exponential growth in cost for increase in the number of points in a trajectory. To put this in context, popular open-source trajectory datasets such as T-Drive and GeoLife contain hundreds of thousands of points in each trajectory. Current works assume the availability of calibrated data or perform calibration prior to analysis[18]. This approach is feasible for small data sets, but will not scale to larger datasets. This problem will only be aggravated by increasing dataset size and real-time analysis requirements.

To tackle this issue, we propose a calibration-aware distance measurement algorithm TRAJEDI in this paper. TRAJEDI selectively calibrates portions of trajectories in a result set to obtain pair-wise distances with better response times and comparable accuracy. We implement and evaluate TRAJEDI with synthetic data to demonstrate the feasibility of our scheme, as well as the effects of tuning parameters to control the trade-off between response time and accuracy. Our main contributions include:

- A calibration-aware distance measurement algorithm that can be used as the building block for analytics techniques such as diversity or k-nearest neighbors (section "How to Write a TRAJEDI")
- Implementation and experimental evaluation of TRAJEDI, our proposed scheme, on synthetic datasets (section "Experimental Evaluation")

The Need for Calibration-Aware Distance

In this section we introduce the Dynamic Time Warping distance function, and the trajectory calibration methods we use. While these are published works, we did not find open source implementations available and hence implemented our own versions. We provide the details of these implementations in this section as well. Finally, we present results from our studies of the cost of calibration on trajectories, demonstrating the need for calibration-aware distance measurements between trajectories. Our results show that computing fully calibrated trajectories scales poorly even on relatively small synthetic data.

Dynamic Time Warping

Dynamic Time Warping (DTW) is a distance measurement metric originally used for time series data when the time domain itself is unimportant to the distance calculation and the time series being measured are different lengths. The metric

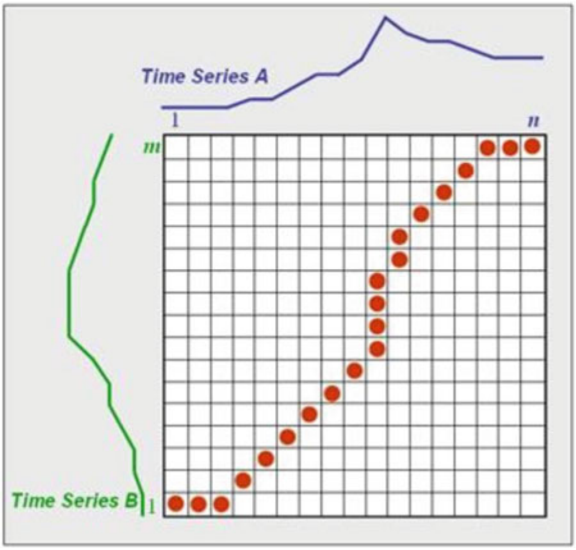

Fig. 8.1 Dynamic time warping matrix

finds the alignment between time series such that the distance between the series is minimized. Alignment in this context means the mapping of points in the first time series to points in the second time series that maintains the ordering of the points. For example, if we have time series x with points x_1, x_2, and x_3, and time series y with points y_1 and y_2. The optimal alignment could be the map $(x_1 \rightarrow y_1, x_2, x_3 \rightarrow y_2)$; however, the map $(x_1, x_3 \rightarrow y_1, x_2 \rightarrow y_2)$ would not be valid due to the mixing of the time order of the points of x.

To efficiently compute this, we employ the standard dynamic programming algorithm which constructs a matrix M of size $n \times m$, where n is the number of points in the first time series, and m is the number of points in the second time series. Within the matrix, an example of which is shown in Fig. 8.1

$$M(i, j) = min\left(M(i-1, j-1), M(i-1, j), M(i, j-1)\right) + D(i, j) \quad (8.1)$$

where D is the distance function. The distance function here is defined as simple Euclidean distance between points i and j. Extending this algorithm to trajectories is done in a straightforward way, where all aspects of the algorithm remain the same, and Euclidean distance is used to compute the distance from point i to point j in the matrix computation.

Grid-Based Calibration

Our calibration technique is a state-of-the-art technique that assumes no underlying properties of the dataset and is thus generally applicable. To begin, a reference set

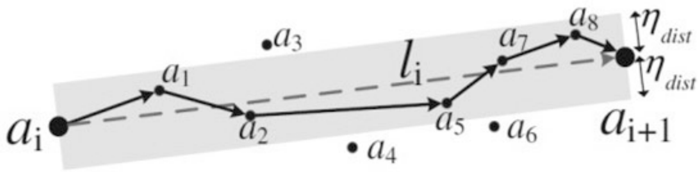

Fig. 8.2 Sample grid based calibration

of points is constructed using a grid based approach. In this, the entire data space is divided into an $N \times N$ grid and anchor points are placed at the center of each square in the grid. These anchor points are then used as the final points that all points of the trajectories will map to after the following two phases of the algorithm: **Alignment** and **Complement**.

The **alignment** phase of the algorithm involves snapping trajectory points to anchor points that are close in distance. In particular, for each trajectory point, a nearest neighbor search is done on the anchor point set to find candidate anchor points that are within a system specified threshold from the current trajectory point. If no anchor points are within this threshold, then the point is removed from the set. If multiple consecutive trajectory points map to the same anchor point, then this anchor point is only treated as a single point in the final calibrated trajectory, thus reducing the dimensionality of the trajectory. A helpful visual from [18] (Fig. 8.2) explains this as well.

The **complement** phase of the algorithm involves data interpolation between consecutive aligned anchor points following the alignment phase. For a given pair of consecutive anchor points, a_1 and a_2, the algorithm first constructs the line segment $\bar{a}$ connecting a_1 and a_2 and finds all points within a specified threshold from $\bar{a}$. Then, it iterates through the points $(p_1, \cdots, p_k)$ in the set ordered by increasing distance from a_1. For each point p_i, p_i is added to the set only if the moving trend of is unchanged during this process. More concretely, the point is added only if the angle between the line $pi1$ to p_i and the line $\bar{a}$ is less than $\frac{\pi}{2}$.

The Cost of Calibration

The issue with the state-of-the-art calibration approach is that it is computationally expensive. Performing the nearest neighbor searches and geometric calculations result in a slow process for large datasets. To illustrate this, we examined the runtime performance of our implementation of the calibration scheme for growing subsets of the T-Drive dataset (Fig. 8.3). In this figure, we see that the time to compute the fully calibrated set of trajectories becomes prohibitively expensive as the set increases. To rectify this situation, we next discuss our scheme for computing trajectory distances while keeping this cost in check.

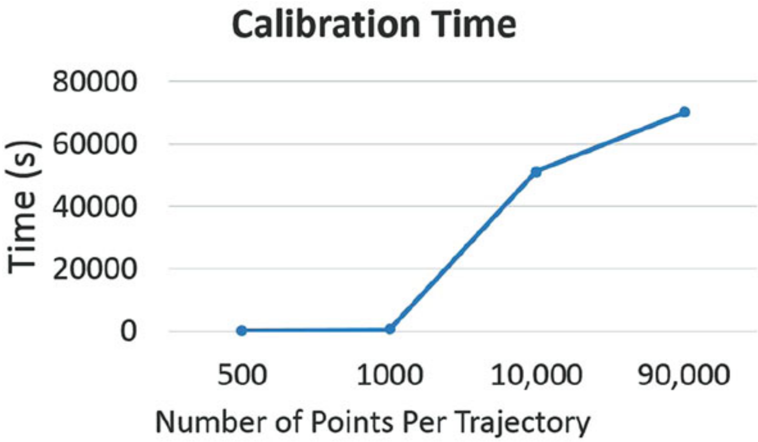

Fig. 8.3 Calibration cost vs. points per trajectory

How to Write a TRAJEDI

In this section, we present TRAJEDI, our scheme for computing pair-wise distances between trajectories that balances accuracy and efficiency. We describe how our scheme works as a calibration aware distance function, including the system design and control flow.

TRAJEDI Scheme

Our scheme for balancing the accuracy-efficiency trade-off between fully calibrated trajectories and uncalibrated trajectories involves using a sliding window over the DTW matrix of a pair of trajectories to determine the most important region of a trajectory to calibrate. Specifically, the method examines the entries located in the diagonal of the DTW matrix at the edge of the sliding window and finds the difference between these entries. In doing so, it determines the location of the trajectory that contributes most strongly to the DTW distance of the overall matrix. The window size is controlled by a parameter α, where $0 < \alpha < 1$ represents the percentage of the overall matrix to be calibrated. High settings of α represent full calibration with low efficiency while low settings of α represent the converse.

More formally, let M be the $n \times m$ DTW matrix, where $n < m$, computed on the raw trajectories $T1$ and $T2$. Then, given input parameter α, the evaluated windows range from point$(1, 1)$, $(\alpha \times n, \alpha \times m)$ to the final window of $(\alpha \times n, \alpha \times m)$, (n, m). The step size for window the n coordinate ranges is 1, where the step size for the m coordinate is $\frac{m}{n}$.

An issue that arises in using this scheme for all pair-wise trajectory distance calculations in a full trajectory dataset is that by the end of the calculations, all trajectories are nearly fully calibrated even for small settings of alpha. This is due to the fact that the DTW calculation is repeated for each trajectory. To alleviate this issue, we insert the requirement that all trajectories will only be calibrated during one DTW calculation with another trajectory. To determine this partner for all trajectories, we suggest some potential schemes that leverage the fact that the DTW matrix is cheap to calculate.

Our baseline scheme is to randomly select one partner from all trajectories to use in the DTW calculation to calibrate the trajectory. We call this baseline **Random**. Our other schemes involve computing the whole pair-wise distance matrix on the raw trajectories, and then using this information to select a partner. We select partners based upon trajectories that are furthest apart, and we call this scheme **Largest/Furthest**, and we select partners based upon the closest trajectories, and we refer to this as **Shortest**.

Experimental Evaluation

In this section we describe how we generated the synthetic data used in the evaluation, the experimental settings, and the various measurements.

Evaluation Data and Setting

Our dataset was simulated by taking an anchor point reference set that was constructed using the method described in section "The Need for Calibration-Aware Distance", with a 1000×1000 grid. Each trajectory began at a randomly selected anchor point and proceeded in a random walk, but only in directions that continued the moving trend of the trajectory or that resulted in no change in the trajectories motion. To simulate the issue of different sampling rates, we used a Gaussian distribution to decide how many points to remove. A small amount of Gaussian noise was injected into each point to simulate the effect of uncertainty in GPS signals.

Our small dataset consisted of 50 trajectories originally with 1500 points. The amount of points in the final version came from $N(800, 200)$, which produces trajectories with significantly differing sampling rates. Our large dataset consisted of 200 trajectories with the same sampling rate values.

The entire system was implemented in Java 1.8 (front end) with PostgreSQL 9.4 serving as the database backend. For these initial experiments, all time costs reported are in terms of processing time, thus ignoring any I/O costs that may be incurred by the database implementation.

Analysis of Results

To evaluate our scheme, we measured both *accuracy* and *efficiency*. *Accuracy* is defined as the effect on results, and *efficiency* captures the total percentage of trajectories calibrated. As baselines for comparison, we use algorithms that perform no calibration and full calibration. Accuracy in these experiments refers to the normalized average difference over entries in the pair-wise distance matrices over all trajectories in the dataset. For these experiments, all accuracy measurements refer to the distance in comparison with the ground truth trajectory dataset before noise is introduced and sampling rates are changed.

First, we evaluate the effects of the window size parameter on accuracy (Fig. 8.5) and efficiency (Fig. 8.5) for different trajectory pair choice selections. In addition, Fig. 8.6 shows how changing the size parameter affects the wall clock time required for the computations to complete.

First, we evaluate the effects of the window size parameter on accuracy (Fig. 8.4) and efficiency (Fig. 8.5) for different trajectory pair choice selections on our small 50 trajectory dataset. The accuracy results are varied with the random choice of trajectory partner performing the best. An interesting result of these experiments is that for middling values of the calibration parameter we see a degradation of accuracy to worse than baseline levels. A possible explanation for this is that a middle window size causes poorer selection of calibration window that reduces the accuracy even though a large percent of the trajectory is calibrated. The efficiency results are as expected in that the percentage of calibrated trajectory points on average is very similar to the setting of the parameter value. In Fig. 8.6 we can see that in terms of absolute wall clock time our scheme delivers improvements in efficiency at the slight cost of accuracy measurements.

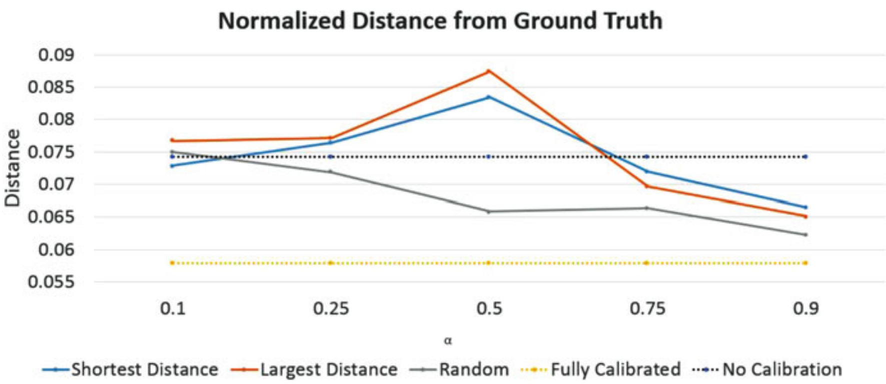

Fig. 8.4 Effect on *accuracy* for window size settings

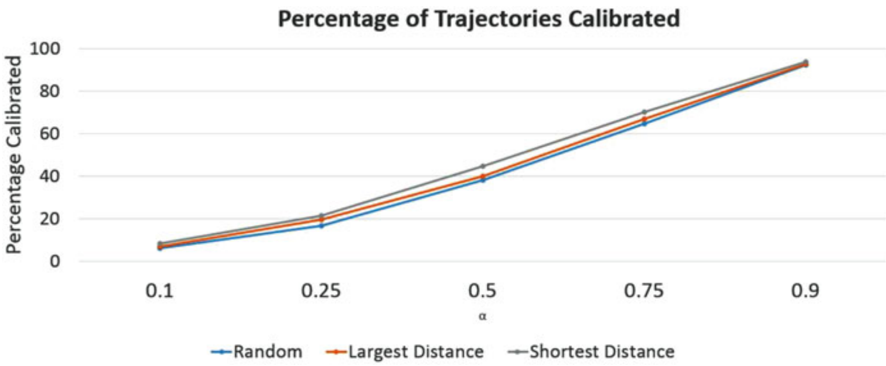

Fig. 8.5 Effect on *efficiency* for window size settings

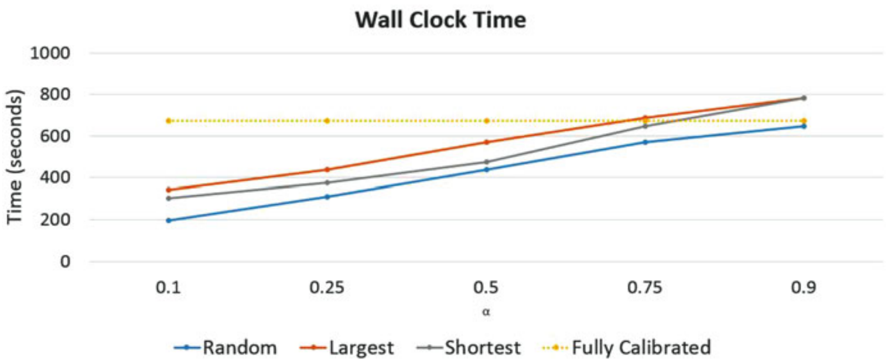

Fig. 8.6 Wall clock time measurements

Next, we compare the performance to the larger 200 trajectory datasets in Figs. 8.7 and 8.8. These experiments demonstrate that the accuracy results from the smaller dataset do not necessarily generalize to other dataset distributions. In particular, we no longer see that middle values of the calibration parameter cause a degradation of performance. In addition, in these experiments we see that choosing a partner to calibrate against based on the one that is furthest away actually provides the best performance. Thus, in terms of accuracy, we conclude that the performance of these various schemes is dataset dependent and further exploration into this needs to be done to have definite conclusions. The efficiency results appear much the same as the smaller 50 trajectory dataset, though in this large dataset smaller settings of the calibration parameter result in a greater percentage of the trajectory being calibrated.

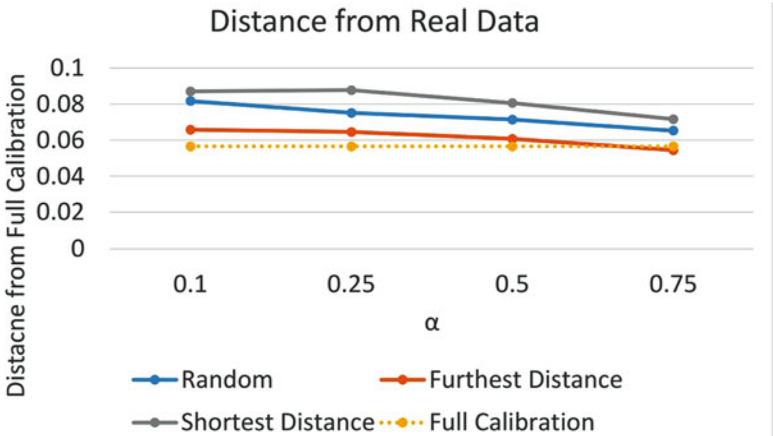

Fig. 8.7 Effect on accuracy for window size settings

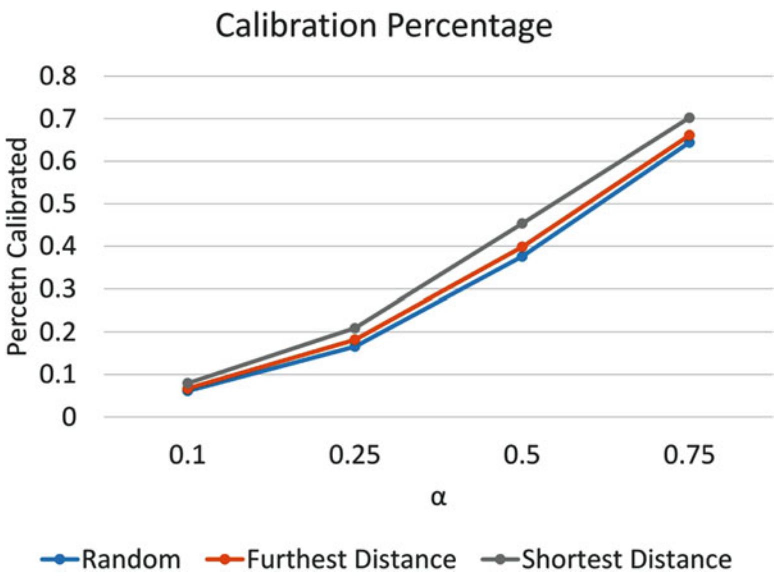

Fig. 8.8 Effect on efficiency for window size settings

Conclusions

In this project, we proposed a calibration-aware distance measurement algorithm, TRAJEDI, which can be used for dissimilarity measurement among trajectories. TRAJEDI can effectively measure the distance between trajectories considering the most influential segment of the trajectories providing robust criterion for dissimilarity estimation of trajectories. Our evaluation demonstrates that we can trade off between the level of desired accuracy and time performance.

Generally, measuring similarity/dissimilarity provides a useful tool for the analysis of trajectories across a wide range of applications. The results of the measurements can be used for wide range of applications such as spatial indexing, equipping analysts with more robust tool for interpretation of pedestrian, vehicle, and animal movement. Using this algorithm for measuring dissimilarity/similarity enables experts and general users of trajectory databases to explore their data more effectively in practical applications.

References

1. Amini, M. H., Boroojeni, K. G., Iyengar, S., Blaabjerg, F., Pardalos, P. M., & Madni, A. M. (2018). A panorama of future interdependent networks: From intelligent infrastructures to smart cities. In *Sustainable interdependent networks* (pp. 1–10). Cham: Springer.
2. Amini, M. H., Boroojeni, K. G., Iyengar, S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks: From theory to application*. Cham: Springer.
3. Bao, J., Zheng, Y., & Mokbel, M. F. (2012). Location-based and preference-aware recommendation using sparse geo-social networking data. In *Proceedings of the 20th International Conference on Advances in Geographic Information Systems* (pp. 199–208). New York: ACM.
4. Bogorny, V., Kuijpers, B., & Alvares, L. O. (2009). ST-DMQL: A semantic trajectory data mining query language. *International Journal of Geographical Information Science, 23*(10), 1245–1276.
5. Chen, L., Özsu, M. T., & Oria, V. (2005). Robust and fast similarity search for moving object trajectories. In *Proceedings of the 2005 ACM SIGMOD International Conference on Management of Data* (pp. 491–502). New York: ACM.
6. Chen, Z., Shen, H. T., & Zhou, X. (2011). Discovering popular routes from trajectories. In *2011 IEEE 27th International Conference on Data Engineering (ICDE)* (pp. 900–911). Piscataway: IEEE.
7. Chen, Z., Shen, H. T., Zhou, X., Zheng, Y., & Xie, X. (2010). Searching trajectories by locations: An efficiency study. In *Proceedings of the 2010 ACM SIGMOD International Conference on Management of Data* (pp. 255–266). New York: ACM.
8. Gharani, P., & Karimi, H. A. (2017). Context-aware obstacle detection for navigation by visually impaired. *Image and Vision Computing, 64*, 103–115.
9. Gharani, P., Suffoletto, B., Chung, T., & Karimi, H. A. (2017). An artificial neural network for movement pattern analysis to estimate blood alcohol content level. *Sensors, 17*(12), 2897.
10. Giannotti, F., Nanni, M., Pedreschi, D., Pinelli, F., Renso, C., Rinzivillo, S., et al. (2011). Unveiling the complexity of human mobility by querying and mining massive trajectory data. *The VLDB Journal: The International Journal on Very Large Data Bases, 20*(5), 695–719.
11. Giannotti, F., Nanni, M., Pinelli, F., & Pedreschi, D. (2007). Trajectory pattern mining. In *Proceedings of the 13th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 330–339). New York: ACM.
12. Javadi, S. H. S., Gharani, P., & Khadivi, S. (2018). Detecting community structure in dynamic social networks using the concept of leadership. In *Sustainable interdependent networks* (pp. 97–118). Cham: Springer.
13. Liu, S., & Meng, X. (2015). A location-based business information recommendation algorithm. *Mathematical Problems in Engineering, 2015*, Article ID 345480.
14. Mohammadi, A., & Dehghani, M. J. (2014). Spectrum allocation using fuzzy logic with optimal power in wireless network. In *2014 4th International eConference on Computer and Knowledge Engineering (ICCKE)* (pp. 532–536). Piscataway: IEEE.

15. Potamias, M., Patroumpas, K., & Sellis, T. (2006). Sampling trajectory streams with spatiotemporal criteria. In *2006 18th International Conference on Scientific and Statistical Database Management* (pp. 275–284). Piscataway: IEEE.
16. Rao, K. V., Govardhan, A., & Rao, K. C. (2012). Spatiotemporal data mining: Issues, tasks and applications. *International Journal of Computer Science and Engineering Survey, 3*(1), 39.
17. Shen, Y., Kwan, M.-P., & Chai, Y. (2013). Investigating commuting flexibility with GPS data and 3d geovisualization: A case study of Beijing, China. *Journal of Transport Geography, 32*, 1–11.
18. Su, H., Zheng, K., Huang, J., Wang, H., & Zhou, X. (2015). Calibrating trajectory data for spatio-temporal similarity analysis. *The VLDB Journal, 24*(1), 93–116.
19. Suffoletto, B., Gharani, P., Chung, T., & Karimi, H. (2018). Using phone sensors and an artificial neural network to detect gait changes during drinking episodes in the natural environment. *Gait & Posture, 60*, 116–121.
20. Vlachos, M., Kollios, G., & Gunopulos, D. (2002). Discovering similar multidimensional trajectories. In *2002 Proceedings 18th International Conference on Data Engineering* (pp. 673–684). Piscataway: IEEE.
21. Wang, Y., Zheng, Y., & Xue, Y. (2014). Travel time estimation of a path using sparse trajectories. In *Proceedings of the 20th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 25–34). New York: ACM.
22. Yin, Z., Cao, L., Han, J., Luo, J., & Huang, T. S. (2011). Diversified trajectory pattern ranking in geo-tagged social media. In *SDM* (pp. 980–991). Philadelphia: SIAM.
23. Yu, X., Pu, K. Q., & Koudas, N. (2005). Monitoring k-nearest neighbor queries over moving objects. In *Proceedings 21st International Conference on Data Engineering. ICDE 2005* (pp. 631–642). Piscataway: IEEE.
24. Yuan, J., Zheng, Y., Xie, X., & Sun, G. (2011). Driving with knowledge from the physical world. In *Proceedings of the 17th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining* (pp. 316–324). New York: ACM.
25. Yuan, J., Zheng, Y., Xie, X., & Sun, G. (2013). T-drive: Enhancing driving directions with taxi drivers' intelligence. *IEEE Transactions on Knowledge and Data Engineering, 25*(1), 220–232.
26. Yuan, J., Zheng, Y., Zhang, C., Xie, W., Xie, X., Sun, G., et al. (2010). T-drive: Driving directions based on taxi trajectories. In *Proceedings of the 18th SIGSPATIAL International Conference on Advances in Geographic Information Systems* (pp. 99–108). New York: ACM.
27. Yuan, J., Zheng, Y., Zhang, L., Xie, X., & Sun, G. (2011). Where to find my next passenger. In *Proceedings of the 13th International Conference on Ubiquitous Computing* (pp. 109–118). New York: ACM.
28. Yuan, N. J., Zheng, Y., & Xie, X. (2012). Segmentation of urban areas using road networks. MSR-TR-2012-65, Tech. Rep.
29. Zheng, Y., Li, Q., Chen, Y., Xie, X., & Ma, W.-Y. (2008). Understanding mobility based on GPS data. In *Proceedings of the 10th International Conference on Ubiquitous Computing* (pp. 312–321). New York: ACM.
30. Zheng, Y., Liu, L., Wang, L., & Xie, X. (2008). Learning transportation mode from raw GPS data for geographic applications on the web. In *Proceedings of the 17th International Conference on World Wide Web* (pp. 247–256). New York: ACM.
31. Zheng, Y., Liu, Y., Yuan, J., & Xie, X. (2011). Urban computing with taxicabs. In *Proceedings of the 13th International Conference on Ubiquitous Computing* (pp. 89–98). New York: ACM.
32. Zheng, Y., Xie, X., & Ma, W.-Y. (2010). Geolife: A collaborative social networking service among user, location and trajectory. *IEEE Data(base) Engineering Bulletin, 33*(2), 32–39.
33. Zheng, Y., & Zhou, X. (2011). *Computing with spatial trajectories*. New York: Springer.

Chapter 9
A Smart Decentralized Vehicle-to-Grid Scheme for Primary Frequency Control

Hamidreza Keshavarz and Mohammad Mohammadi

Nomenclature

t	Real time
t_{pin}	Plug-in time of the EV (h)
t_{pout}	Plug-out time of the EV (h)
SOC	Real-time state of charge of the EV battery
SOC_{min}	Minimum state of charge of the EV battery
SOC_{max}	Maximum state of charge of the EV battery
SOC_{in}	Initial state of charge of the EV battery
$SOC_{desired}$	Desired state of charge of the EV battery
SOC_{tpout}	State of charge at the plug-out time of the EV battery
E_r	Rated capacity of the EV battery (kWh)
P_{max}	Maximum power limit of the EV battery charger
K	V2G gain
K_c	Charging V2G gain
K_d	Discharging V2G gain
K_{max}	Maximum V2G gain

Introduction

In order to enable proper operation of power systems, the frequency should be kept roughly at nominal value. The frequency of the power system is a common factor throughout the system that depends on the balance between the active power supply and demand. The imbalance between the active power supply and demand will lead to the frequency deviation in the power system [1].

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Power systems are nowadays faced with opportunities and challenges. It is because penetration of renewable energy sources (RESs) in the power systems is increased due to environmental considerations and limited fossil fuel reserves [2]. Production of these sources has an intermitted nature. Hence, maintaining the balance between power supply and demand in the power system which means keeping the frequency at nominal value is an important challenge.

Due to energy storage capability and quick response in power delivery/absorption to/from the grid, the previous studies have addressed the use of battery energy storage to deal with the challenge [3–8].

Many electric vehicles (EVs) have high energy storage potential in their batteries and considerable plug-in time to the grid. This is a compelling reason to use the plug-in electric vehicles (PEVs) to improve the grid performance (vehicle-to-grid (V2G)) in general and the frequency regulation in particular. The aforementioned issue can act as an economic incentive to people to increase the use of EVs.

Due to the current energy storage capability of many EVs, researchers seek for ways to use the aggregated EVs to improve the grid performance effectively [9–13]. Currently, the EVs are controlled in most studies centrally. Then, they will be suitable to participate in load-frequency control (secondary frequency control (SFC)).

Fast response of the EV battery in absorbing and delivering power may introduce them as effective candidates for use in the primary frequency control (PFC). Frequency is a common factor throughout the system. Therefore, monitoring the battery charger output frequency helps to become aware of the grid status and decide to take the required actions participating in frequency control. When demand outpaces supply in power system, the frequency is reduced. In [14], to deal with the frequency reduction, in addition to the governor's reaction, there is a cessation in EV charging. In this case, the attention is mostly attracted to the grid than to the EV user's satisfaction. An EV user tends to maintain the desired EV state of charge (SOC) at the plug-out time (scheduled SOC) so that the driver can follow his/her daily schedule.

In [15], similar to conventional generators the droop control with constant gain is adopted to enable participation of PEV in PFC. To achieve the scheduled SOC, a constant scheduled charging power is considered. In this way the power for the PFC is not under the control and depends on the grid frequency deviations. This power might ruin the scheduled charging and make overcharging and overdischarging of the EV battery. In [16], in using the droop control, the controller gain reaches zero with ramp slope in maximum and minimum SOCs which protects the EV battery from overcharging and overdischarging. In [17], the V2G control based on droop control is proposed to keep SOC of 50%. In this scheme, the proportional controller gain is selected adaptively and depends on the SOC of the EV battery. In [18], charge balance control has been developed for charging balance in the initial SOC.

In general, charging the EV battery is not possible by charge balance control scheme. As the proportional controller gain is smaller than its maximum value, the full capacity of the PEV is not used to improve the frequency of the grid. Furthermore, the charging balance happens if we assume that the average of the frequency deviations is zero. The average frequency deviation during the plug-in time may not always be truly zero. For example, if during the plug-in time the load decreases/increases, the average frequency deviations will be positive/negative during this period.

This study proposes a smart decentralized V2G control scheme based on droop control for participating PEV in the PFC. In the proposed scheme, droop control with smart gain is adopted to enable participation of EV in the PFC and charging load reference signal is also considered to achieve the scheduled SOC for EV battery.

Using the proposed scheme: (1) The EV battery reaches the desired SOC at the plug-out time (scheduled SOC) at the same time when it participates in the PFC. The grid frequency deviations do not have any influence on this goal. (2) The EV battery is prevented from overcharging and overdischarging and (3) the possible extent is used to the maximum capacity of the PEV in the PFC.

The structure of this chapter is as follows: In section "Overall Structure of Frequency Control" the overall frequency control structure of a sample power system where the EVs have been integrated is described. In section "Proposed Decentralized V2G Control Scheme" the proposed smart decentralized V2G control scheme is presented. The details of analyzed system are given in section "Simulation System." Simulations and discussions to illustrate the performance of the proposed scheme are in section "Simulations and Discussions." Finally, section "Simulation of the Proposed Scheme" concludes the chapter.

Overall Structure of Frequency Control

Active power and reactive power flows are almost independent of each other and are influenced by different control actions. Maintaining load-generation balance leads to keeping frequency at nominal value. Figure 9.1 shows the model of this behavior in a sample power system in the operating point.

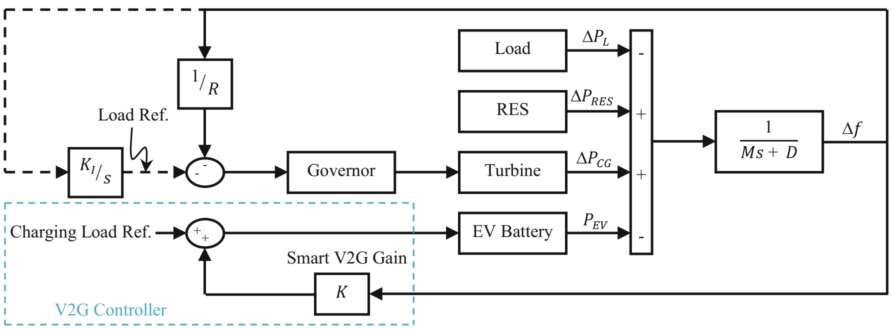

Fig. 9.1 Block diagram of the sample power system for the frequency control

Power mismatch between supply and demand leads to the frequency deviation. Transfer function, in turn, depends on the total inertia constant of the system ($H = M/2$) and the load damping constant (D).

In the analyzed system, the load and the generation of the RESs are selected unpredictably. These factors will be the causes of mismatch between supply and demand.

Generally, to deal with the frequency deviation in the illustrated system in Fig. 9.1, conventional generators are equipped with two control loops. The PFC loop in a conventional generator is characterized as a proportional controller with a gain of $1/R$. In a conventional generator, this controller shows a fast response to the frequency deviations which is coordinated with responses of other generators. Further, a frequency droop remains in the steady state. The SFC loop eliminates the frequency droop remained from PFC in the power system. This control signal follows the load supplied by the conventional generator. That is why this signal is called the load reference (full descriptions are found in [1]).

In the power system of Fig. 9.1, the PEV are also used to provide the PFC. Similar to conventional generators, the droop control is deployed. In the proposed scheme, the primary objectives of the V2G control (which includes scheduled charging, preventing the EV battery from overcharging and overdischarging and enabling maximum utilization of capacity of the PEV in the PFC) have caused the proportional controller gain (V2G gain) to be selected smartly. The charging load reference signal produces the power signal which is required to achieve the scheduled SOC of the EV battery at any moment (full details about V2G controller are given in section "Proposed Decentralized V2G Control Scheme").

Proposed Decentralized V2G Control Scheme

Figure 9.2 shows the detail structure of the proposed decentralized V2G control scheme. According to this figure, the droop control is adopted to enable the participation of the EV in the PFC. The charging load reference signal is also

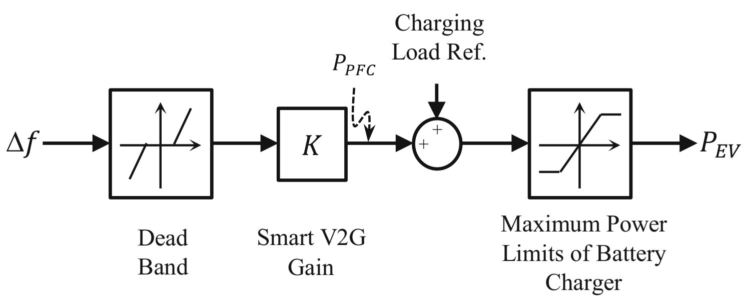

Fig. 9.2 The general structure of the decentralized V2G control scheme

considered to achieve the scheduled SOC for the EV battery. These two control signals are sent to the battery charger. Finally, the EV battery absorbs/injects P_{EV} from/to the grid. The dead band is used to prevent the EV battery from frequent charging and discharging. The saturation block is adopted to model the maximum power limits of the battery charger.

The power for the PFC (P_{PFC}) depends on the grid frequency deviation which is not controllable. Thus we can say that the constant scheduled charging power does not guarantee that the EV battery reaches the scheduled SOC. In the proposed V2G scheme for the EV battery to reach the scheduled SOC, the charging power is exploited as flexible resource. The value of the charging power at any moment guarantees that the EV battery reaches the scheduled SOC. This control signal is called the charging load reference. The charging load reference signal (the essential power for the EV battery to reach the scheduled SOC) is calculated by Eq. (9.1):

$$P_c = \frac{E_{ess}}{T_{res}} \tag{9.1}$$

where E_{ess} is the essential energy for the EV battery to reach the scheduled SOC and T_{res} is the residual time until the plug-out time that are calculated as Eqs. (9.2 and 9.3), respectively:

$$E_{ess} = ((SOC_{desired} - SOC)/100) \times E_r \tag{9.2}$$

$$T_{res} = t_{pout} - t \tag{9.3}$$

The real-time SOC is calculated as follows [10, 18]:

$$SOC = SOC_{in} + \left(\left(\int_{t_{pin}}^{t} P_{EV} dt\right)/E_r\right) \times 100 \tag{9.4}$$

Deploying Eq. (9.1) for the charging power minimizes the effect of power exchange between the EV battery and the grid for the PFC on the scheduled charging. When the EV battery power is injected to the grid for the PFC, the consumed energy of the EV battery will sustain by increasing the charging power during the residual time until the plug-out time. In case the EV battery absorbs power from the grid for the PFC, the EV battery's absorbed energy returns to the grid by decreasing the charging power during the residual time until the plug-out time.

However, the EV battery will reach the scheduled SOC if the battery charger is able to exchange the essential power of the EV battery (calculated from Eq. 9.1) between the EV battery and the grid. If the essential power of the EV battery exceeds the maximum power limits of the battery charger, it will not be able to absorb/inject the essential power of the EV battery from/to the grid. Accordingly, the EV battery will fail to reach the scheduled SOC.

Considering the above information, the power for the PFC (V2G gain) will have restrictions such as:

1. It does not make the essential power of the EV battery exceeding the maximum power limits of the battery charger.
2. It does not make overcharging and overdischarging of the EV battery.

In Fig. 9.2, to support the PFC, the V2G gain value should always be positive. It is obvious that the more is the V2G gain value, the more is the PFC assistance. Further, the zero V2G gain value causes no power exchange between the EV battery and the grid for the PFC. Hence, no assistance will be provided for the PFC.

In order to prevent overcharging and overdischarging of the EV battery by power for the PFC, we need the V2G gain be selected as shown in Fig. 9.3, i.e., the V2G gain is fixed and equal to the maximum V2G gain. The charging V2G gain value in the maximum SOC and the discharging V2G gain value in the minimum SOC are equal to zero. These values, respectively, protect the EV battery from overcharging and overdischarging (the ramp slope is adopted to avoid abrupt changes and its value is determined by the constant parameter of *a*).

To prevent the essential power of the EV battery from exceeding the maximum power limits of the battery a charger is enough; at the moment when the essential power of the EV battery reaches the maximum power limits of the battery charger, the V2G gain in Fig. 9.3 is plated into Fig. 9.4. Because if the real-time SOC is lower than the desired SOC, the essential power of the EV battery is in the charging direction of the EV battery and must be absorbed from the grid. To prevent an

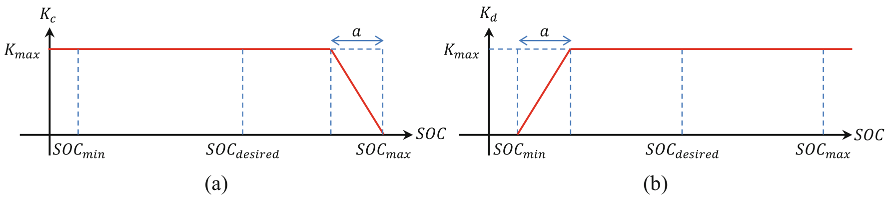

Fig. 9.3 The proposed V2G gain to use the maximum capacity of the PEV for the PFC and protect the EV battery from overcharging and overdischarging. (**a**) The charging gain of V2G. (**b**) The discharging gain of V2G

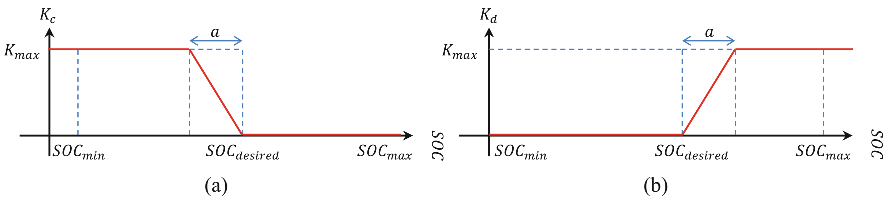

Fig. 9.4 The proposed V2G gain to prevent the calculated charging power from exceeding the maximum power limits of the battery charger. (**a**) The charging gain of V2G. (**b**) The discharging V2G gain

increase in the essential power of the EV battery, no power should be injected from the EV battery into the grid for the PFC. Therefore, the discharging V2G gain must reach zero. When the real-time SOC is higher than the desired SOC, the essential power of the EV battery is in the discharging direction of the EV battery and must be injected to the grid. To prevent a decrease in the essential power of the EV battery, no power should be absorbed by the EV battery from the grid for the PFC. Accordingly, the charging V2G gain must reach zero. This change should occur at the moment when the essential power of the EV battery reaches the maximum power limits of the battery charger. The time when the essential power of the EV battery arrives to the maximum power limits of the battery charger (switching time (t_s)) is calculated by Eq. (9.1):

$$\text{if } t = t_s \rightarrow P_c = \pm P_{max}$$

$$\pm P_{max} = \frac{E_{ess}}{t_{pout} - t_s} \tag{9.5}$$

We find absolute magnitude from the sides of the equation:

$$|\pm P_{max}| = \left| \frac{E_{ess}}{t_{pout} - t_s} \right| \tag{9.6}$$

Since $t_{pout} - t_s > 0$ is always true, we have:

$$P_{max} = \frac{|E_{ess}|}{t_{pout} - t_s}$$

$$t_s = t_{pout} - \frac{|E_{ess}|}{P_{max}} \tag{9.7}$$

Therefore, to guarantee that the EV battery reaches the scheduled SOC, the curve of the V2G gain should be changed from Fig. 9.3 to Fig. 9.4 at t_s. To eliminate sudden changes in this transition, the parts of the V2G gain curve that their value needs to reach zero at t_s should start to decrease from the maximum V2G gain before t_s (e.g., $t_s - b$, where b is a small constant), until they reach zero at t_s. To apply this control process to the V2G gain, we define a new parameter, d, which is a function of time. The value of d at any moment represents the distance between zero and parts of V2G gain curve that require to reach zero at t_s. Thus, according to the above information, d should be selected according to Fig. 9.5a. As it is shown in Fig. 9.5, when d is equal to K_{max}, the curves of (1) (marked in Fig. 9.5) represent the V2G gain that the V2G gain will be the same as in Fig. 9.3. In this case, the EV battery is available with the highest level of participation in the PFC. From the moment $t_s - b$ the d value decreases, until the parts of the V2G gain curve that need to reach zero at t_s start decreasing. In this context, the amount of the EV's participation in the PFC

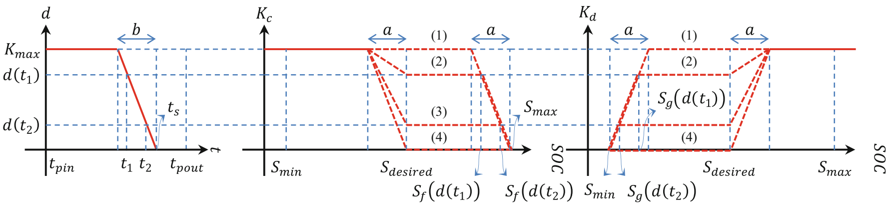

Fig. 9.5 The smart V2G gain for the proposed scheme. (**a**) The smart *d* parameter. (**b**) The charging V2G gain. (**c**) The discharging V2G gain (to avoid crowding: S has been used instead of SOC)

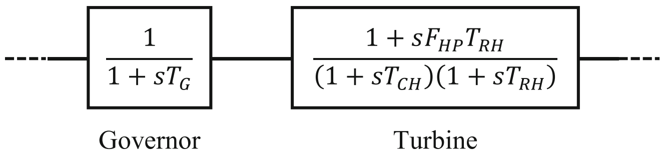

Fig. 9.6 Block diagram of the governor and the turbine of the thermal power plant

will also decline. For instance, when d is equal to $d(t_1)$, the curves of (2) (marked in Fig. 9.5) represent the V2G gain. At the moment t_s, the value of d reaches zero. At this moment the curves of (4) (marked in Fig. 9.5) represent the V2G gain and the V2G gain will be the same as in Fig. 9.4. At this moment also the EV's participation in the PFC reaches zero. Because as it is shown in Fig. 9.4 if the real-time SOC is lower than the desired SOC, the discharging V2G gain reaches zero and as a result the EV battery for the PFC injects no power into the grid. Also at this moment (t_s) the essential power of the EV battery reaches the maximum positive power limit of the battery charger. As a result, the EV battery absorbs no power from the grid for the PFC. Thus, from this moment (t_s) the EV does not participate in the PFC (the above-mentioned issues are also extensible for situations where the real-time SOC is higher than the desired SOC).

The input parameter for the V2G gain calculated based on Fig. 9.5a:

$$d = \begin{cases} 0, & t < t_{\text{pin}} \\ K_{\max}, & t_{\text{pin}} \le t < t_{\text{s}} - b \\ \frac{-K_{\max}}{b}\left(t - t_{\text{s}}\right), & t_{\text{s}} - b \le t < t_{\text{s}} \\ 0, & t_{\text{s}} \le t \end{cases} \tag{9.8}$$

Considering Fig. 9.6, the V2G gain in the proposed scheme is formulated as below:

$$K = \begin{cases} K_{\text{c}}, & \Delta f \ge 0 \\ K_{\text{d}}, & \Delta f < 0 \end{cases} \tag{9.9}$$

where

$$K_c = \begin{cases} K_{max}, & SOC \le SOC_{desired} - a \\ \frac{d-K_{max}}{a}\left(SOC - \left(SOC_{desired} - a\right)\right) + K_{max}, & SOC_{desired} - a < SOC \le SOC_{desired} \\ d, & SOC_{desired} < SOC \le SOC_f \\ \frac{-K_{max}}{a}\left(SOC - SOC_{max}\right), & SOC_f < SOC \le SOC_{max} \\ 0, & SOC_{max} < SOC \end{cases} \tag{9.10}$$

SOC_f is

$$SOC_f = d\left(\frac{a}{-K_{max}}\right) + SOC_{max} \tag{9.11}$$

and

$$K_d = \begin{cases} 0, & SOC \le SOC_{min} \\ \frac{K_{max}}{a}\left(SOC - SOC_{min}\right), & SOC_{min} < SOC \le SOC_g \\ d, & SOC_g < SOC \le SOC_{desired} \\ \frac{K_{max}-d}{a}\left(SOC - \left(SOC_{desired} + a\right)\right) + K_{max}, & SOC_{desired} < SOC \le SOC_{desired} + a \\ K_{max}, & SOC_{desired} + a < SOC \end{cases} \tag{9.12}$$

SOC_g is

$$SOC_g = d\left(\frac{a}{K_{max}}\right) + SOC_{min} \tag{9.13}$$

In the proposed scheme, the charging load reference signal is obtained by Eq. (9.1) and the smartV2G gain is derived from Eqs. (9.9–9.13). This helps the EV battery to reach the scheduled SOC under any conditions, and also protects the EV battery from overcharging and overdischarging.

Simulation System

For simulation of the proposed smart decentralized V2G control scheme, the EV is integrated in a sample power system. The production capacity is 400 kW in this power system where 50% of the power production is supplied by the RESs. As shown in Fig. 9.1, the dynamic model of the power system is used for calculating the system frequency. The total inertia constant of the system ($H = M/2$) and the load damping constant (D) are, respectively, considered equal to 5 s and 1% [1]. In this study, the dynamics of the RESs and the load are ignored. Thermal power plant is characterized by turbine and governor models. The turbine and governor

Table 9.1 Thermal power plant simulation parameters

Parameters	R	K_I	T_G	T_{CH}	T_{RH}	F_{HP}
Value	0.05	0.1	0.2 s	0.3 s	7.0 s	0.3

Table 9.2 V2G simulation parameters

Parameters	Value
Battery capacity	40 kWh
Maximum power limits of battery charger	10 kW
Minimum/maximum SOC	10/90
Dead band of frequency	0.01 Hz
Maximum V2G gain	100 kW/Hz
a	5
b	100 s

blocks are shown in Fig. 9.6. The thermal power plant simulation parameters are summarized in Table 9.1 [1].

In Fig. 9.2 the proposed smart decentralized V2G control scheme is shown in more detail. Here, in the scheme, the charging load reference signal is selected based on Eq. (9.1) and the V2G gain is determined based on Eqs. (9.9–9.13). The V2G simulation parameters are summarized in Table 9.2.

Simulations and Discussions

The simulated system is implemented in MATLAB Simulink environment.

Simulation of the Proposed Scheme

To demonstrate the effectiveness of the proposed V2G scheme, two simulation scenarios were considered.

(a) Scenario A.1: Under normal conditions.

In this scenario, the changes of the RES production and the load during a day are typically selected in a time series and are, respectively, shown in Fig. 9.7a, b. The plug-in time of the EV is assumed to be 8:00 a.m. and the plug-out time is considered to be 4:00 p.m. The initial SOC and the desired SOC of the EV were obtained by the normal distribution within the limits, as brought in Table 9.3.

In simulation, the obtained initial and desired SOC are, respectively, 25% and 74%. As shown in Fig. 9.8, the proposed scheme is quite successful in assisting the EV battery to reach the scheduled SOC. The SOC has reached 74% at the plug-out time. The frequency deviation in the presence of the EV has improved, as well. The results of this scenario are summarized in Table 9.4.

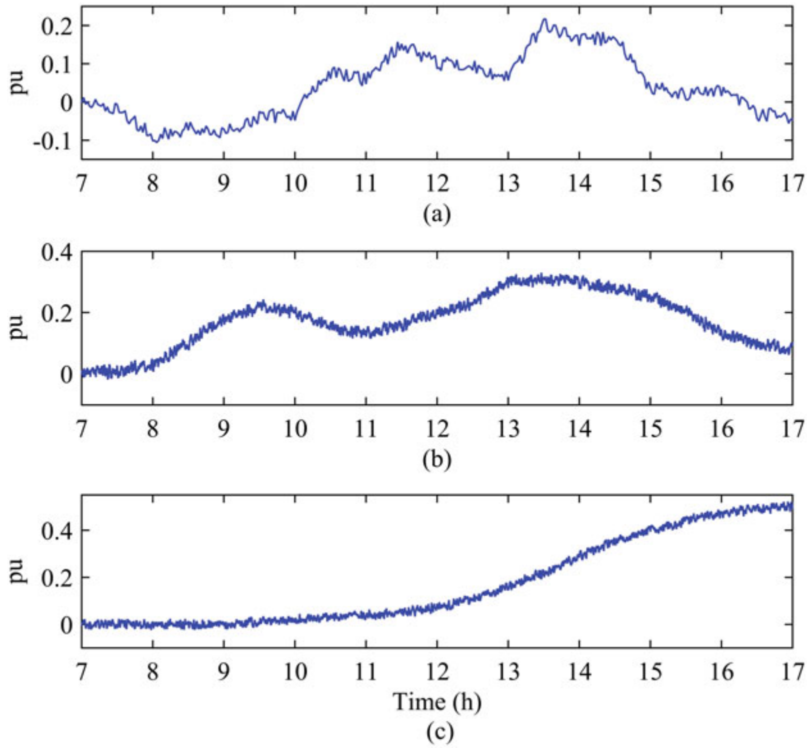

Fig. 9.7 Changes of the load and the RES production. (**a**) Changes of the RES production. (**b**) Changes of the typical load. (**c**) Changes of the increasing load

Table 9.3 Simulation results: scenario A.1

Simulation	SOCin	SOCdesire	SOCtpout	RMS Δf (Hz)
Proposed scheme	25	74	74	0.03319
Without EVs	–	–	–	0.04572

(b) Scenario A.2: Under the worst conditions.

In this scenario, the changes of the load during 1 day in a time series are selected as in Fig. 9.7c where the load is ascending. The production of the RESs, the initial SOC, and the desired SOC of the EV were selected as in *scenario A.1*. To worsen the conditions, the plug-in duration has become shorter. The plug-in and the plug-out time of the EV are assumed to be 2:00 p.m. and 4:00 p.m., respectively.

In simulation, the obtained initial and desired SOC are, respectively, 35% and 77%. As shown in Fig. 9.9, the proposed scheme is quite successful in assisting the EV battery to reach the scheduled SOC. The SOC has reached 77% at the plug-out time. The frequency deviation in the presence of the EV has improved, as well. Since the load is increasing, the EV battery has injected power into the grid for the PFC.

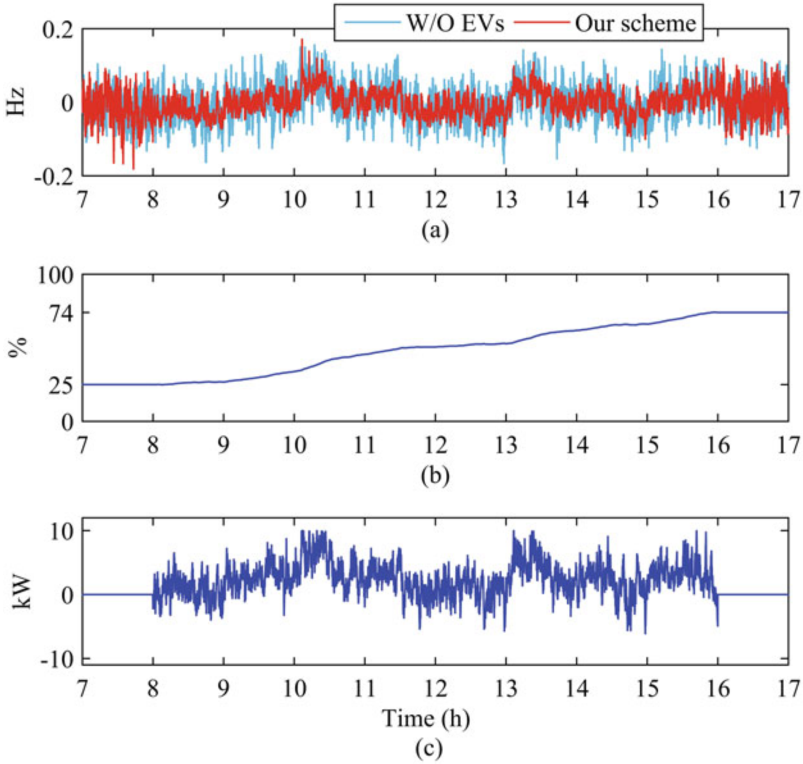

Fig. 9.8 Scenario A.1. (**a**) The grid frequency deviation. (**b**) The real-time SOC of the EV. (**c**) The exchanged power between the EV battery and the grid

Table 9.4 Simulation results: scenario A.2

Simulation	SOCin	SOCdesire	SOCtpout	RMS Δf (Hz)
Proposed scheme	35	77	77	0.04758
Without EVs	–	–	–	0.05119

This issue has caused the essential power of the EV battery to increase and reach the maximum positive power limit of the battery charger ($P_c = 10$ kW). According to the previous discussions, at this moment, the EV's participation has reached zero. The results of this scenario are summarized in Table 9.5.

Comparisons and Discussions

To compare the proposed scheme with the previous schemes in this field, the scheme of droop control with constant gain and constant scheduled charging power

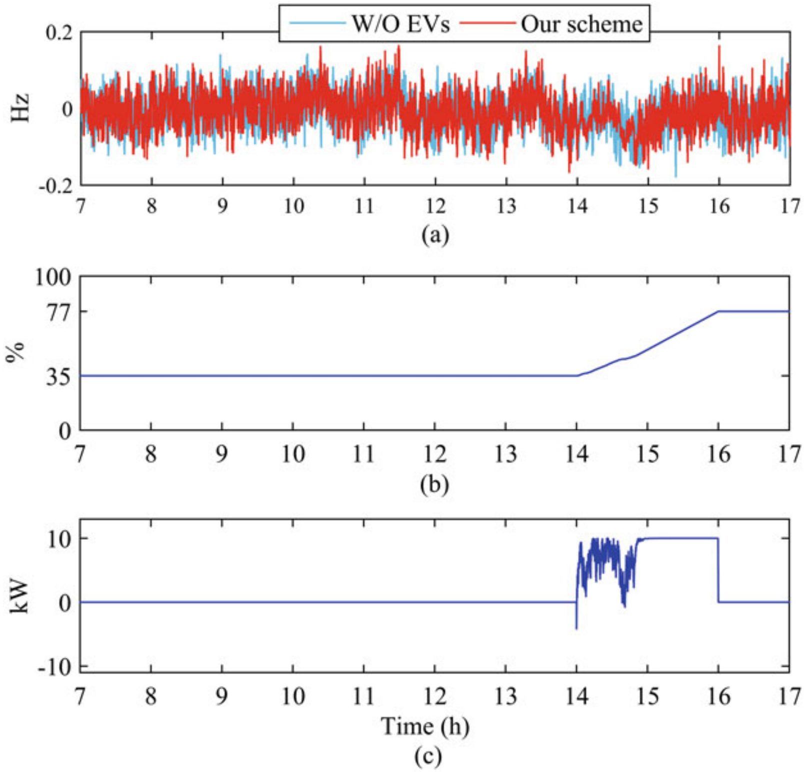

Fig. 9.9 Scenario A.2. (**a**) The grid frequency deviation. (**b**) The real-time SOC of the EV. (**c**) The exchanged power between the EV battery and the grid

Table 9.5 Simulation results: scenario B.1

Simulation	SOCin	SOCdesire	SOCtpout	RMS Δf (Hz)
Proposed scheme	80	80	80	0.03327
Scheme in [15]	80	80	68.70	0.03281
Scheme in [18]	80	80	73.08	0.03628
Without EVs	–	–	–	0.04543

presented in [15] and the charge balance control scheme presented in [18] are particularly selected.

The changes of the RES production and the load are selected, respectively, as in Fig. 9.7a, c. Since the proposed scheme in [18] is only used to maintain the SOC of the EV battery in its initial value, two scenarios are considered here.

(c) Scenario B.1: Maintaining the SOC of the EV batteries.

In this scenario, the initial SOC of the EV is considered 80%. It is assumed that the EV user tends to have the SOC of the EV battery kept at the plug-out time in its

Table 9.6 Simulation results: scenario B.2

Simulation	SOCin	SOCdesire	SOCtpout	RMS Δf (Hz)
Proposed scheme	20	80	80	0.03363
Scheme in [15]	20	80	68.29	0.03308
Without EVs	–	–	–	0.04543

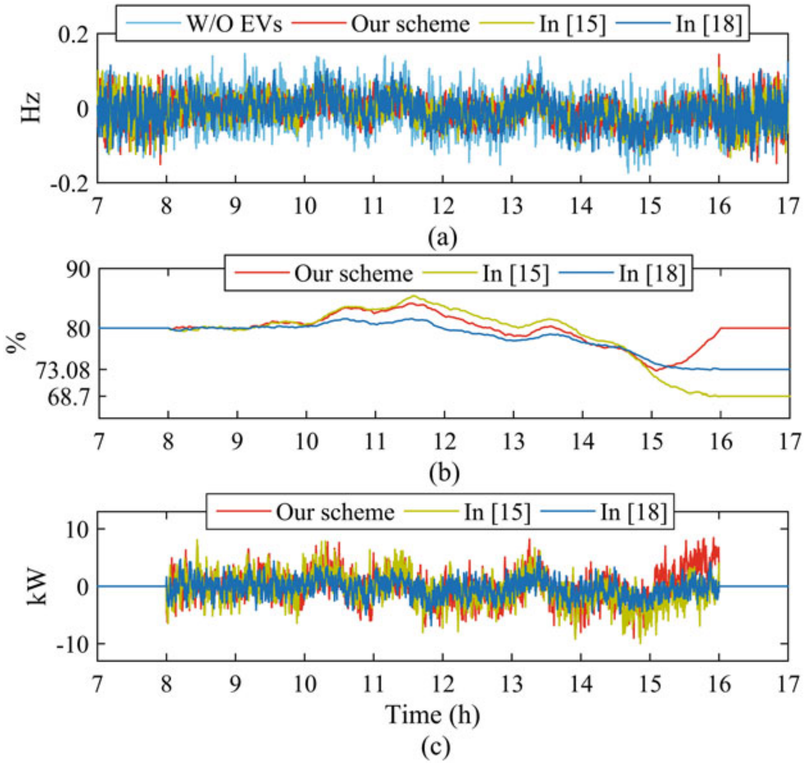

Fig. 9.10 Scenario B.1. (**a**) The grid frequency deviation. (**b**) The real-time SOC of the EV. (**c**) The exchanged power between the EV battery and the grid

initial value. The plug-in and the plug-out time of the EV are considered 8:00 a.m. and 4:00 p.m., respectively.

Considering the results of the simulation in Table 9.6 and as shown in Fig. 9.10, only the proposed scheme is able to bring the SOC of the EV battery at the plug-out time to its initial value (i.e., the desired value). In the proposed scheme, the recorded SOC of the EV battery at the plug-out time is 80%. An ascending increase in the load has caused the average frequency deviation and the average exchanged power between the EV battery and the grid for the PFC to become negative. This issue has made the schemes in [15, 18] fail to maintain the SOC. In schemes [15, 18], the recorded SOCs at the plug-out time are 68.70% and 73.08%, respectively. Since the proposed scheme and the scheme in [15] have always participated with the

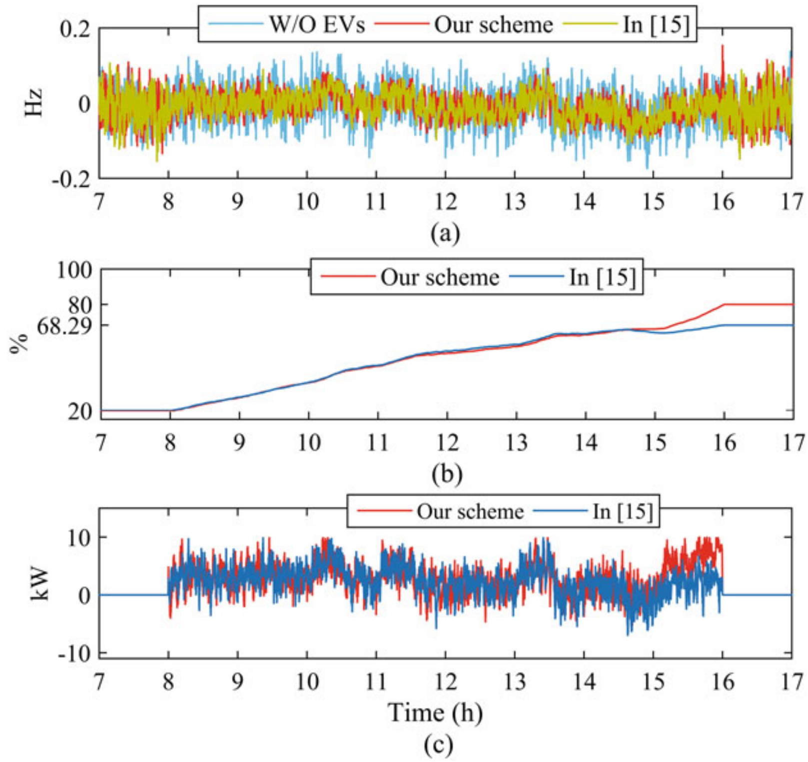

Fig. 9.11 Scenario B.2. (**a**) The grid frequency deviation. (**b**) The real-time SOC of the EV. (**c**) The exchanged power between the EV battery and the grid

maximum V2G gain value in the PFC, the frequency is more improved compared to the proposed scheme in [18].

(d) Scenario B.2: Charging of the EV batteries.

In [18] for the EV charging the proposed scheme in [15] is used. Therefore, in this scenario the proposed scheme is compared with the proposed scheme in [15]. In this scenario, the initial SOC of the EV is considered 20% and at the plug-out time the EV user tends to experience the SOC of 80%. The plug-in and the plug-out time of the EV are assumed to be 8:00 a.m. and 4:00 p.m., respectively.

Considering the results of the simulation in Table 9.7 and as shown in Fig. 9.11, only the proposed scheme is able to bring the SOC of the EV battery to the desired value at the plug-out time. In the proposed scheme, the recorded SOC of the EV battery at the plug-out time is 80%. An ascending increase in the load caused the average frequency deviation to become negative and made the scheme [15] fail to bring the EV battery to the scheduled SOC. In the scheme [15], the recorded SOC of EV battery at the plug-out time is 68.29%. The frequency improvements in the proposed scheme and the scheme in [15] performed well. It is because both schemes have always participated in the PFC with the maximum V2G gain value.

Conclusion

In this chapter, a decentralized V2G control scheme was proposed for the PFC which considers the satisfaction of EV drivers. Each EV in the proposed scheme participates in the PFC to the possible extent without using communication lines and achieves the scheduled SOC. To this end, similar to the conventional generators, droop control is deployed. It is with the difference that droop coefficient is selected smartly until, together with the flexible charging power, it (1) guarantees the EV battery to reach the scheduled SOC, (2) uses the PEV in the PFC to the possible extent, and (3) prevents the EV battery from overcharging and overdischarging.

Due to simulation in the previous schemes, the grid conditions are influential in bringing the EV battery to the scheduled SOC. Nevertheless, in the proposed scheme, the EV battery will reach the scheduled SOC under any grid conditions.

References

1. Kundur, P., Balu, N. J., & Lauby, M. G. (1994). *Power system stability and control* (Vol. 7). New York: McGraw-Hill.
2. Chowdhury, S., & Crossley, P. (2009). *Microgrids and active distribution networks*. Stevenage: The Institution of Engineering and Technology.
3. Lu, C.-F., Liu, C.-C., & Wu, C.-J. (1995). Effect of battery energy storage system on load frequency control considering governor deadband and generation rate constraint. *IEEE Transactions on Energy Conversion, 10*(3), 555–561.
4. Lopes, J. A. P., Moreira, C. L., & Madureira, A. G. (2006). Defining control strategies for micro grids islanded operation. *IEEE Transactions on Power Systems, 21*(2), 916–924.
5. Wu, D., Tang, F., Dragicevic, T., Vasquez, J. C., & Guerrero, J. M. (2014). Autonomous active power control for Islanded AC microgrids with photovoltaic generation and energy storage system. *IEEE Transactions on Energy Conversion, 29*(4), 882–892.
6. Mahmood, H., Michaelson, D., & Jiang, J. (2015). Decentralized power management of a PV/battery hybrid unit in a droop-controlled Islanded microgrid. *IEEE Transactions on Power Electronics, 30*(12), 7215–7229.
7. Tang, X., Hu, X., Li, N., Deng, W., & Zhang, G. (2016). A novel frequency and voltage control method for Islanded microgrid based on multienergy storages. *IEEE Transactions on Smart Grid, 7*(1), 410–419.
8. Karimi, Y., Oraee, H., Golsorkhi, M. S., & Guerrero, J. M. (2017). Decentralized method for load sharing and power management in a PV/battery hybrid source islanded microgrid. *IEEE Transactions on Power Electronics, 32*(5), 3525–3535.
9. Escudero-Garzas, J. J., Garcia-Armada, A., & Seco-Granados, G. (2012). Fair design of plug-in electric vehicles aggregator for V2G regulation. *IEEE Transactions on Vehicular Technology, 61*(8), 3406–3419.
10. Masuta, T., & Yokoyama, A. (2012). Supplementary load frequency control by use of a number of both electric vehicles and heat pump water heaters. *IEEE Transactions on Smart Grid, 3*(3), 1253–1262.

11. Pillai, J. R., & Bak-Jensen, B. (2011). Integration of vehicle-to-grid in the Western Danish power system. *IEEE Transactions on Sustainable Energy, 2*(1), 12–19.
12. Han, S., Han, S., & Sezaki, K. (2010). Development of an optimal vehicle-to-grid aggregator for frequency regulation. *IEEE Transactions on Smart Grid, 1*(1), 65–72.
13. Liu, H., Hu, Z., Song, Y., Wang, J., & Xie, X. (2015). Vehicle-to-grid control for supplementary frequency regulation considering charging demands. *IEEE Transactions on Power Systems, 30*(6), 3110–3119.
14. Mu, Y., Wu, J., Ekanayake, J., Jenkins, N., & Jia, H. (2013). Primary frequency response from electric vehicles in the Great Britain power system. *IEEE Transactions on Smart Grid, 4*(2), 1142–1150.
15. Almeida, P. M. R., Lopes, J. A. P., Soares, F. J., & Seca, L. (2011). Electric vehicles participating in frequency control: Operating islanded systems with large penetration of renewable power sources. *2011 IEEE Trondheim PowerTech, Trondheim*, 1–6.
16. Izadkhast, S., Garcia-Gonzalez, P., & Frías, P. (2015). An aggregate model of plug-in electric vehicles for primary frequency control. *IEEE Transactions on Power Systems, 30*(3), 1475–1482.
17. Ota, Y., Taniguchi, H., Nakajima, T., Liyanage, K. M., Baba, J., & Yokoyama, A. (2012). Autonomous distributed V2G (Vehicle-to-Grid) satisfying scheduled charging. *IEEE Transactions on Smart Grid, 3*(1), 559–564.
18. Liu, H., Hu, Z., Song, Y., & Lin, J. (2013). Decentralized vehicle-to-grid control for primary frequency regulation considering charging demands. *IEEE Transactions on Power Systems, 28*(3), 3480–3489.

Part III
Sustainable Power Networks

Chapter 10
Demand Response in Future Power Networks: Panorama and State-of-the-art

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Introduction

Overview

One of the key features of future power networks, referred to as smart grids, is deploying demand-side resources in order to reduce the stress at the supply side. This implies active participation of electricity customers, as a societal network, in the power networks, as a physical network, which increases the interdependencies of these two networks due to the effect of demand response programs on power systems. Furthermore, in the future smart cities there is a crucial need to take advantage of demand-side resources to supply electricity in a sustainable manner. In

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this context, demand response programs play a pivotal role in electricity market in order to achieve supply-demand balance by taking advantage of the load flexibility.

In this chapter, we provide a thorough review of the state-of-the-art approaches to implement demand response programs in smart grid environment. To this end, we first introduce the available methods to model load participation in terms of demand response programs, such as game theoretic frameworks, price elasticity, and direct load control. We then review the methods for integrating demand-side resources into power systems. Several aspects of demand response programs are reviewed in this chapter. Finally, an overview of the recent advances in demand response literature is presented.

Available Methods to Model the Demand Response Programs

Demand response programs are defined as the end users' activities to change the electricity consumption pattern for mitigating the system problems [1]. Due to the increased consumption level, these programs are attractive and beneficial for system operators, as well as customers [2, 3].

In order to assess the impact of demand response programs (DRPs) on power system studies, multifarious models are developed in recent years. Economic models of responsive loads based on the concept of constant price elasticity have been addressed in references [4–8]. Schweppes and his co-workers developed the concept of spot pricing of electricity to evaluate variable costs of electric energy on an hourly basis and proposed three responsive load models, namely linear, potential, and exponential demand functions [9]. A customers' response to the optimal real-time prices has been modeled in [10] for the electricity applying multifarious mathematical load models. An optimization model to adjust the hourly load level of a given consumer in response to hourly electricity prices is proposed in [11]. The

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further study utilizes up/down ramping rates to model variation in customer load. An approval function based on the acceptable energy costs for different clusters of customers has been presented in [12]. Moreover, the customer's behavior versus the offered fixed prices for monthly bilateral contracts applying a type of market share function is proposed in [13]. Reference [14] has employed analytical and technical approach to validate the impact of DRPs. Customer baseline load (CBL) focusing on administrative and contractual approaches is applied for DRP modeling in [15]. Moreover, the impact of demand response (DR) through optimization methods has been presented in [11]; however, intelligent approach such as multi-agent-based and fuzzy logic method is used to model demand response [16, 17]. Authors in [18] have developed two markets for designing DRPs to match power supply and demand. DR models based on participation information of DRRs which are suggested in [18] can be useful for evaluating DR resources' values. Kirschen showed how this model could be taken into consideration when scheduling generation and setting the price of electricity in a pool-based electricity market [19]. Market clearing programs are discussed in [20, 21], which takes their economic benefits into account. An economic model of responsive loads has been derived and used for multifarious studies in [22–32]. In references [22–32], the elasticity of demand is considered as a fixed value for different values of incentive and penalty, which cannot precisely represent the customers' behavior. Therefore, in [33], extracting a dynamic economic model of responsive loads is suggested based upon the concept of "flexible elasticity of demand" and "customer benefit function." Indeed, under the smart grid environment, the short-term elasticity of demand can be suggested. Therefore, introducing the flexible elasticity as a consequence of smart electricity grids causes more precise modeling of DRPs and hence decrease in the rate of consumption coincides with the ISO perspectives from implementing demand response programs. References [4–33] have not assumed that demand response resources might fail or be perfidious to decrease their consumption. In other words, the previous studies have not concentrated that demand response resources are unstable, changeable, and unpredictable. Additionally, advanced metering infrastructure (AMI) system as a part of growing smart grid initiatives provides significant foundational platforms for demand response resources in response to the demand response events. It means that any destruction in AMIs can affect demand response resource's participation while this serious matter has not been regarded in previous demand response models. In reference [34], a systematic method based upon frequency and duration approaches is utilized to present the multi-state modeling of multiple demand response resources considering repairable advanced metering infrastructure, the so-called demand response firm. In reference [34], a set of DRRs such as homes, industrials, and large buildings, which have the potential of participating in demand response programs and communicate with demand response aggregator through AMIs, are introduced as a negawatt demand response firm (DRF). DRF is assumed as a virtual power plant that is similar to conventional units with derated output states. The failure and repair rates of AMIs are non-negligible in customers' participation in demand response programs. In this regard, the impact of several important factors like demand response firms' maximum achievable potential and forced outage rate of advanced metering infrastructure on the proposed model is assessed. Also, the effect of number of advanced metering infrastructure on the distribution probability of demand response firm states is investigated in [34].

Amini et al. [35] proposed a multi-agent framework for load management in smart power distribution networks. In their framework, they modeled the distributed generation units as well as direct load control to achieve a peak reduction-based load management strategy. Moreover, a residential load management strategy was proposed by Amini et al. [36] for the home appliances using mixed-integer linear programming. Demand response programs may also affect the behavior of electric vehicle drivers; for instance, different pricing strategies (e.g., real-time pricing, time-of-use pricing, and critical peak pricing) can considerably affect the behavior of drivers [37]. Another aspect of implementing demand response programs is maintaining end-user privacy [38] and prevent adversaries from accessing the private information of customers.

Emerging Methods to Model Demand Response Programs

To make an easier interaction among customers and ISO for performing DR, DR aggregators have been introduced. Likewise, DR aggregators play an important role to achieve all targets of DR implementation such as reducing peak demand, improving the power system security, decreasing the negative effects of renewable energy sources (RESs), uncertainties on power system operation, and enhancing economic aspects of the electricity market. In fact, DR aggregators are as an interface among customers and ISO to enter customers into the wholesale market.

In [39], the interaction among independent system operator (ISO) and DR aggregators has been presented through four options including load curtailment (LC), load shifting (LS), onsite generation, and energy storage (ES) systems. In this method, DR aggregators submit the aggregated DR offers to ISO. Therefore, ISO makes the final decision about DR contribution in a day-ahead market through mixed-integer linear programming. This program has been solved by minimization of total operation cost. The framework of this model is demonstrated in Fig. 10.1.

On the other hand, the interaction between DR aggregators and customers has been taken into account in [40]. In this research work, the small or medium scale of customers offered their potential to participate in the market. In fact, the DR aggregators proposed four options including LC, LS, ES, and onsite generation to customers for hourly demand response. Through maximization of DR aggregators' profit, optimum DR schedule for participation in the day-ahead energy market is obtained. This model is outlined in Fig. 10.2.

In [41], on the one hand, the interaction between ISO and DR aggregators and on the other hand the interaction between DR aggregators and customers have been taken into account, separately. The behavior of customers in DR programs including LC, LS, and load recovery (LR) has been considered through a scenario-based participation factor. Moreover, uncertain prices were presented in day-ahead and

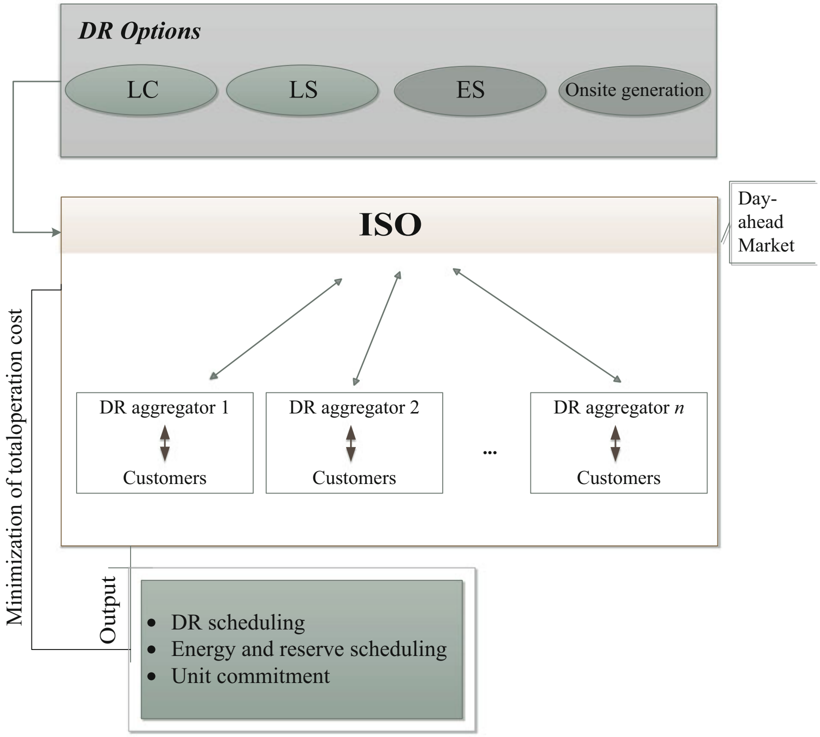

Fig. 10.1 Framework model of reference [39]

balancing markets as well as predefined prices in forward contracts for trading share of DR between ISO and DR aggregators. This model is shown in Fig. 10.3.

The interaction between load-serving entity (LSE) and customers is formulated in a bilevel programming in [42]. In this model, LSE is the leader, and DR aggregators are the followers. LSE serves flexible loads with dynamic pricing tariff and inflexible loads with the fixed tariff. Flexible loads are integrated by some DR aggregators. Therefore, interaction among LSE and DR aggregators is in upper level and the interaction among DR aggregators and customers is in the lower level. Finding the optimal pricing tariff is the solution of this problem. The model is described as a flowchart in Fig. 10.4.

To reduce the impact of thermal generation unit ramping cost on operation cost, hourly demand response program is proposed in [43] in a day-ahead market. Balancing constraints, ramp constraints, and DR constraints are formulated in a mixed-integer quadratic constrained programming for a day-ahead scheduling. The Lagrange relaxation method to solve this problem is shown in Fig. 10.5.

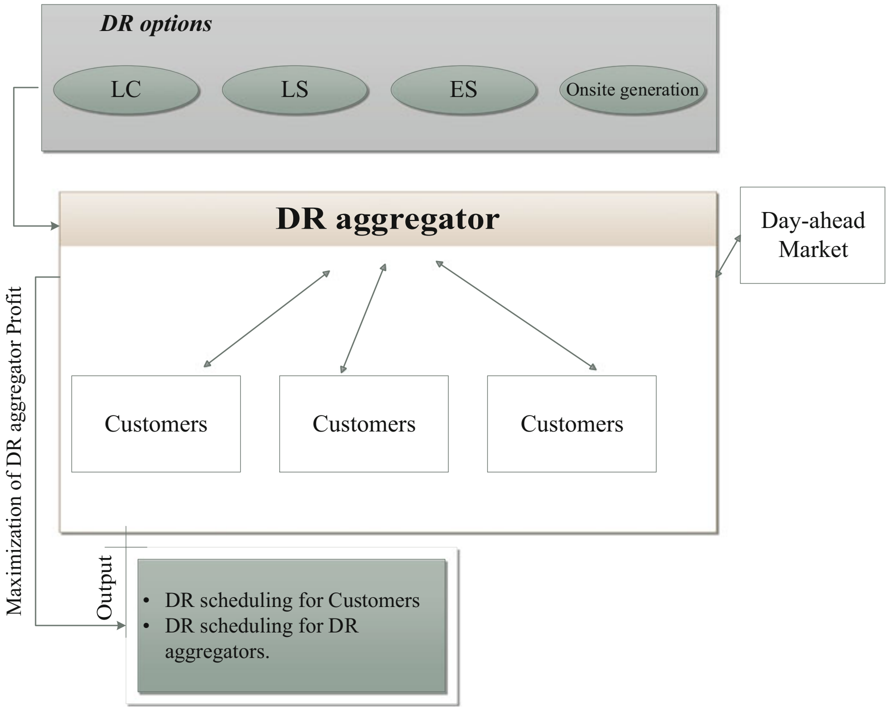

Fig. 10.2 Model of the reference [40]

The Integration of Demand Response Programs with Other Power System Models

Three different kinds of demand response programs including centralized co-optimization of generation and demand, demand bidding, and coupling of renewable energy resources (RES) with deferrable loads have been applied in [44] to evaluate the impact of large-scale RES penetration and demand response on reserve scheduling. In fact, a stochastic unit commitment is run in a network with large-scale RES to obtain the reserve requirements for three different kinds of demand response. Moreover, the coupling of these demand response programs to cope with the weakness of each one has been evaluated. The model is described in the flowchart of Fig. 10.6.

In [45], a dynamic market mechanism has been proposed to get the market equilibrium by dynamic negotiations among key market players. Meanwhile, DR is presented to overcome the variability of renewables. This market mechanism considers DR devices based on the magnitude, runtime, and constraints of demands. The level of desired social welfare has been analyzed eventually by a combination of DR devices in the presence of renewables.

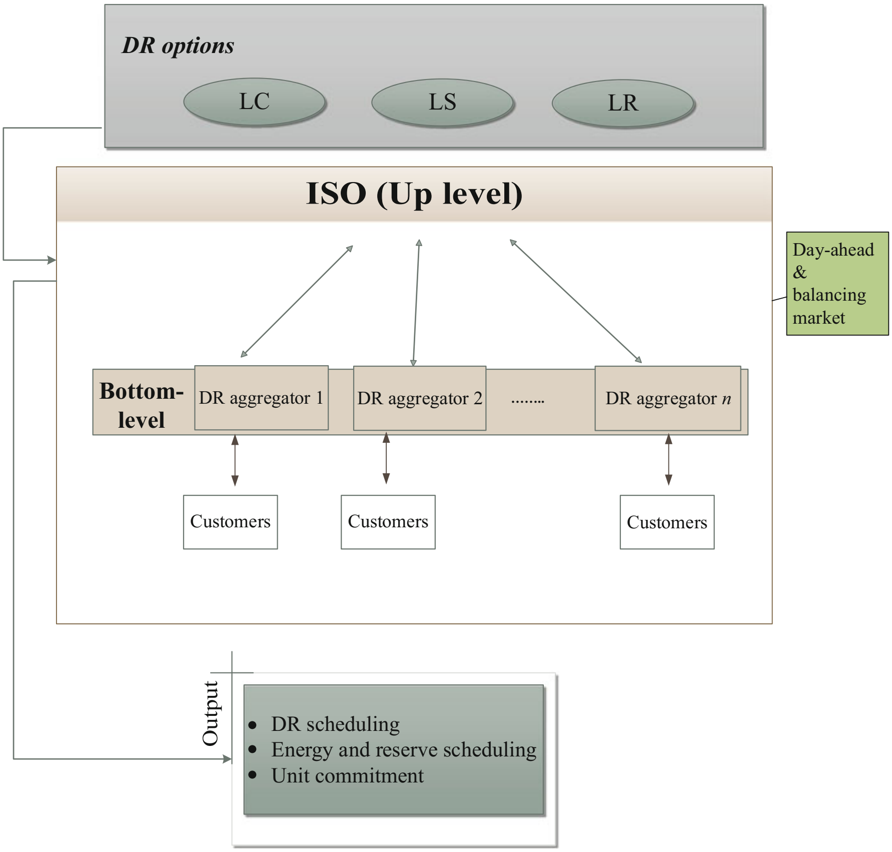

Fig. 10.3 Flowchart of model [41]

The optimal behavior of plug-in electric vehicle (PEV) parking lots is presented in [46] for energy and reserve market. To this end, parking lots are considered as responsive loads either in price-based or incentive-based demand response programs. Therefore, the effects of different demand response programs on parking lots are elaborated, and the participation level of parking lots in demand response programs can be obtained. A stochastic programming has been applied to solve this problem by considering electricity market and PEV uncertainties.

Amini et al. [47] modeled the effect of electricity price on the electric vehicle owner's behavior. There have been several studies to investigate the role of electric vehicles in demand response applications [48–50]. Paper [51] evaluates the unsupervised charging of plug-in electric vehicles (PEVs) at the dwellings. It presents a statistical modeling and a closed-form statistical expression for PEVs' uncoordinated expected charging power demand. A distributed demand response (DR) technique is proposed and evaluated for residential vehicle-to-grid (V2G)-enabled PEVs during their random connection times to the power grid in [52]. The

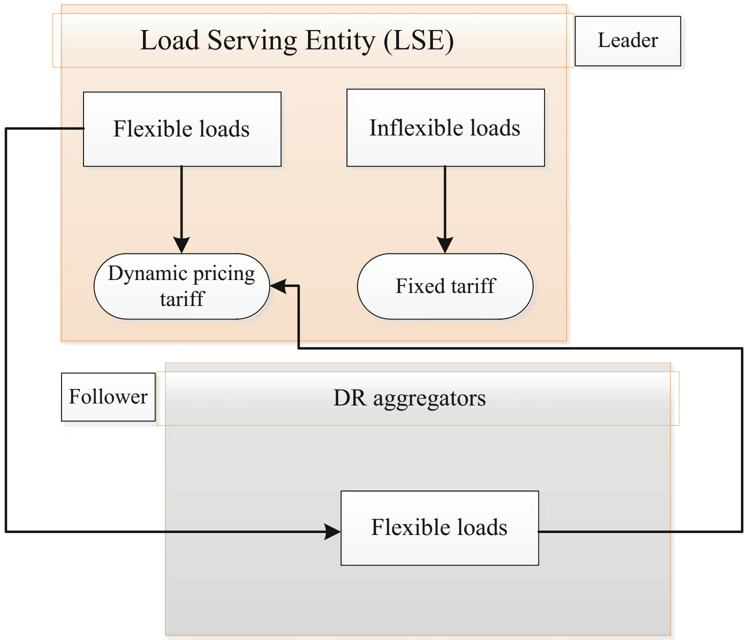

Fig. 10.4 Proposed model in reference [42]

authors show that their proposed fast converging and distributed DR algorithm is successful in managing the charging tasks of 1000 PEV users in order to minimize the peak of the aggregated daily power demand profile and make the peak demand even the same as when there is no PEVs in the system without any changes in the users' commuting behaviors and by preserving their privacy.

In [53, 54], a decentralized algorithm is shown for managing V2G-enabled PEVs' electricity assignments (charging and discharging) to lower the overall electricity procurement costs for electricity retailers bidding to operational day-ahead (DA) and real-time (RT) markets. The proposed algorithm jointly uses DA demand shaping and RT demand altering for the DA and the RT markets, respectively.

The importance of reducing the emissions of greenhouse gases (GHGs) has been captured in the proposed DR technique by the authors of [55]. They illustrate that with some incentives and/or regulations from the power system regulator, the retailers or aggregators could help lessen GHG emissions by using their proposed decarbonized demand response (DDR) technique.

The impacts of demand response on the reliability of power systems through different electricity market mechanism have been analyzed in [56] from technical, economic, and environmental aspects. The main goal of this work is to provide the balancing active power, enhance system reliability, and maintain grid stability through demand response in different electricity market schemes. Different demand response programs based on the market are presented in Fig. 10.7.

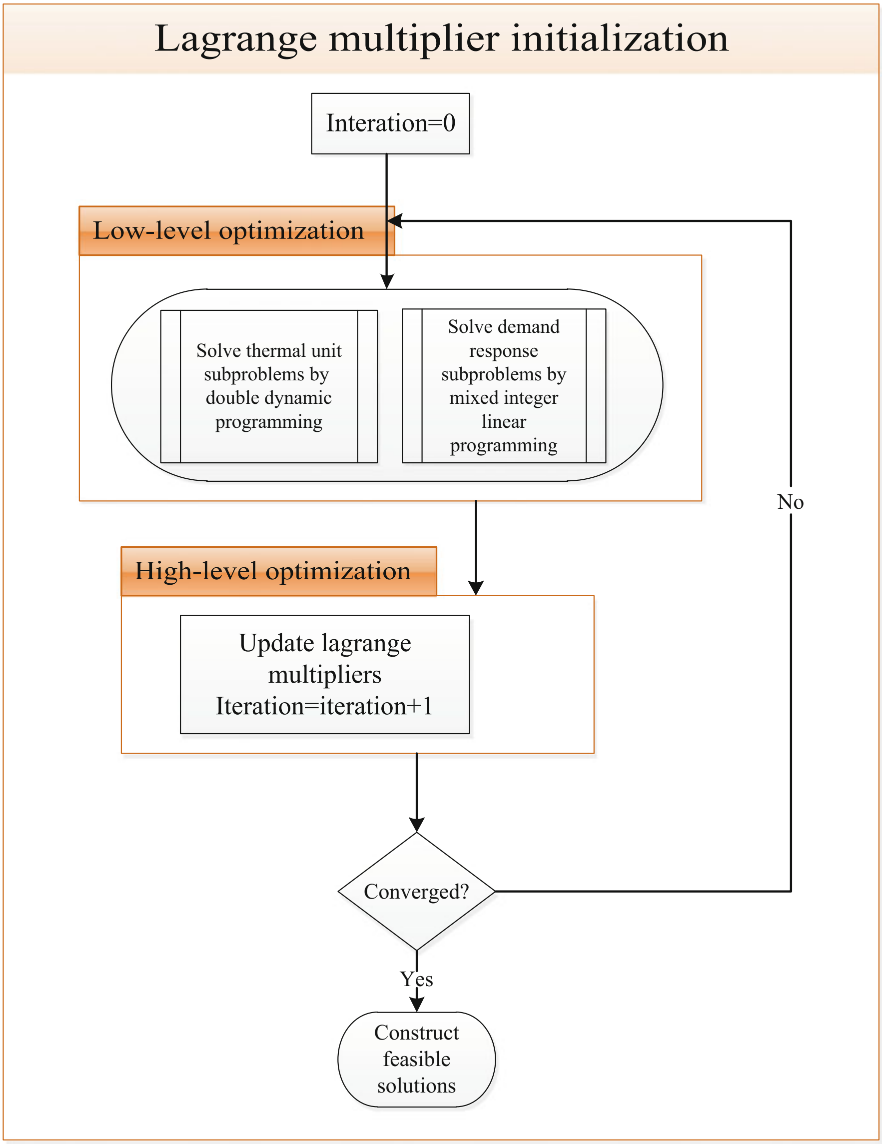

Fig. 10.5 Proposed LR method in reference [43]

Therefore, power system reliability, which can be dropped due to unexpected generation or transmission line outages, can increase by applying demand response programs in the electricity market instead of some conventional approach from generation side.

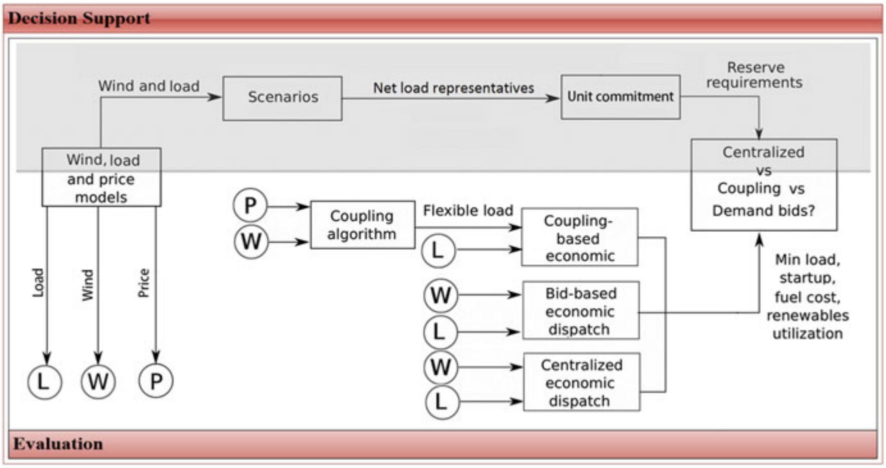

Fig. 10.6 Flowchart of model [44]

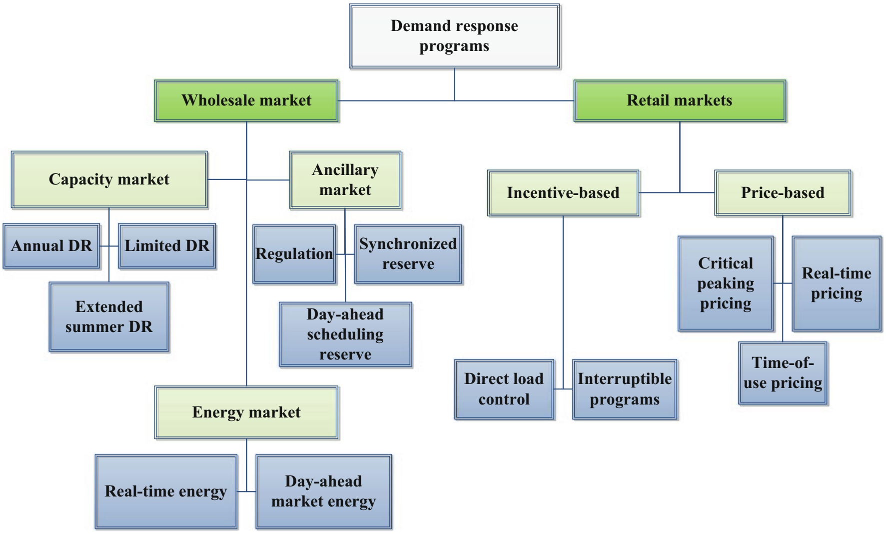

Fig. 10.7 Demand response programs based on markets [56]

In [57], a stochastic day-ahead scheduling for a microgrid has been conducted, and the impact of ancillary service demand response program on total operation cost has been studied. Stochastic nature of RESs including wind farms and photovoltaic systems as well as loads has been considered through Monte Carlo simulation method and generation of lots of scenarios. Likewise, the outage probability of distribution generators (DGs) inside the microgrid and probability of disconnection of upstream network and microgrid have been included through this approach.

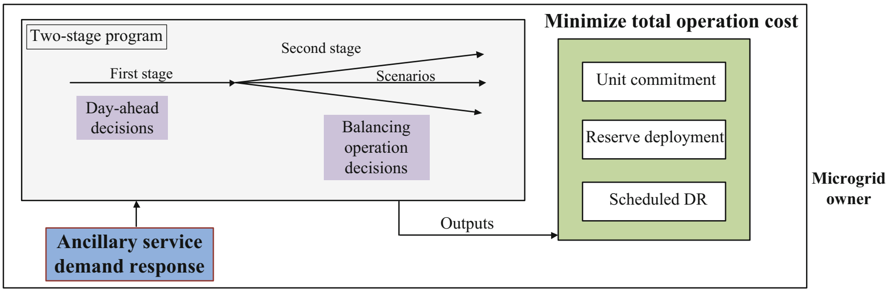

Fig. 10.8 The framework of proposed model in [57]

The problem has been solved by a stochastic two-stage programming in a mixed-integer linear programming. To this end, in the first stage, the day-ahead market is cleared through and there is a look at different scenarios for balancing market in the second stage. The framework of proposed model is presented in Fig. 10.8.

The Effect of Demand Response Programs on the Short-Term Participation Strategy

In a short-term perspective, electricity market participants deal with bidding and offering strategy problem every day. They should trade energy in the day-ahead market in a high level of uncertainty. In such conditions, they can increase their profit by devising a proper method for their participation strategy. These methods have been widely reported and analyzed in the literature [58–62]. These methods help the decision maker to analyze the market and its uncertainties economically.

In addition to the economic tools, electricity companies can get benefit from physical sources and contracts. For example, bilateral contracts can effectively reduce the risk of participation in the day-ahead market [63]. Self-generation is a perfect option for retailers to hedge the risk of buying energy from the uncertain day-ahead market [64]. Hybrid companies that manage generation companies in one side and retailers and load aggregators on the other sides can strongly control the associated risk of day-ahead market [58–60].

Demand response programs (DRPs) can also be used as an effective tool for reducing the risk of participation strategy of electric companies in the short-term day-ahead market. Hybrid companies can use the advantages of DRPs in their offering strategy methods. The diagram of hybrid companies is provided in Fig. 10.9. As can be seen from this figure, the hybrid companies are managing both of generation and retail sides, together. There is an internal energy transaction between these two parts. The external energy in the generation company (GenCo) is sold in the day-ahead market. The retail part submits its bids to the day-ahead market to buy the external consumption. The retail side has two types of contract

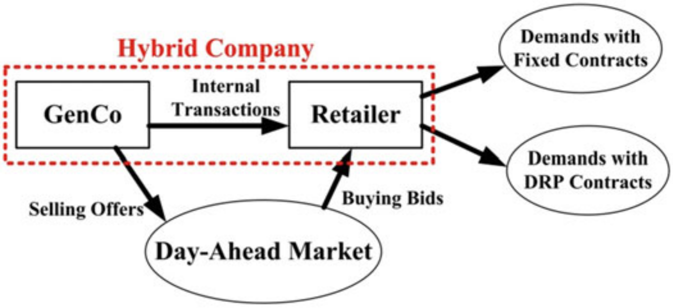

Fig. 10.9 Diagram of hybrid companies considering DRP contracts

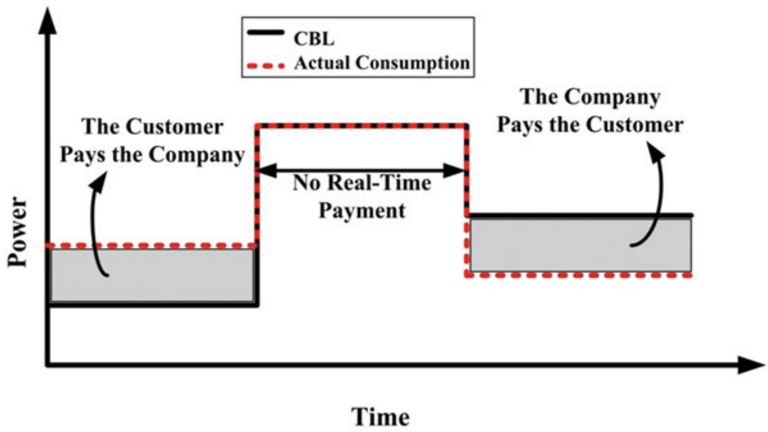

Fig. 10.10 Real-time payments of DA-RTP program

with its clients. The first one is regular contract based on the fixed pricing, and the second one is DRP-based contract.

It is worth to mention that only short-term DRPs can affect the short-term bidding and offering strategy of electricity companies. The longer term DRPs such as time-of-use programs are known during the scheduling horizon of 1 day. As an example of short-term DRPs, the day-ahead real-time pricing (DA-RTP) can be mentioned in which the predicted prices of day-ahead market are sent to the contracted loads, 1 day before operation, to schedule their consumption. In DA-RTP contracts, the customers' base load (CBL), which is defined base on the consumption history of clients, is used to calculate real-time payments [58–60]. This process is better illustrated by Fig. 10.10. In this figure, the CBL and actual consumption are plotted for a 3-hour horizon. As can be seen, during the first interval the real consumption is higher than contracted level of CBL. Thus, the customer should pay the extra consumption to the company base on the real-time prices sent to him/her, 1 day before. This procedure is reversed during the third interval. In this period, the company will charge the client's account base on day-ahead prices. During the second interval in which the consumption is exactly equal to the contracted CBL, no real-time payment is considered.

In order to analyze the effect of DA-RTP programs on the short-term participation strategy of hybrid companies, we have divided them into two categories, price-taker and price-maker companies. The following subsections investigate this effect separately.

The Effect of DA-RTP Programs on Price-Taker Companies

Comparing to the whole network capacity, a price-taker company is small enough in the size that its bidding or offering strategy would not affect the market price. Therefore, it is common in the literature for such companies to use the prediction of day-ahead prices to evaluate the optimum participation strategy [58]. The diagram of this method is simply provided by Fig. 10.11.

From this figure, the forecasted day-ahead prices are the input of two blocks. The upper one models the behavior of DA-RTP-contracted clients. For this purpose elasticity coefficients can be used to calculate the actual level of consumption in the retail side [65]. The second block uses both of predicted prices and actual consumptions to evaluate the optimum schedule for the generation units and the retail side.

In this way, DA-RTP programs can be considered as a feedback in the short-term scheduling of electricity companies. For example, during the days that day-ahead price is forecasted to be high, it is more profitable for the company to sell more power in the market instead of feeding the contracted loads of retail side. In this situation, the DA-RTP program would reflect the high level of the next day's price to the customers and they will reduce their consumptions to get benefit. In this way, the company would have more capacity to participate in the day-ahead market. This situation is reversed during the low-price days. It can be concluded that DA-RTP programs can reduce the risk of uncertain prices. DA-RTP programs will compensate the level of contracted loads in a way to be profitable for the company.

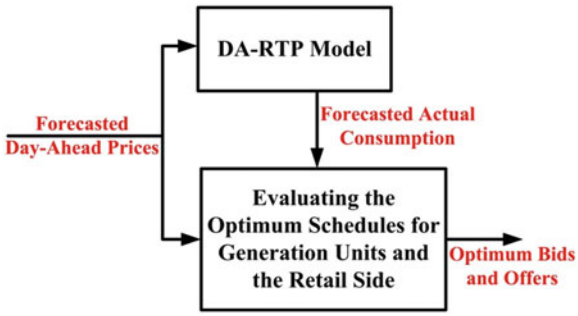

Fig. 10.11 The diagram of DA-RTP programs on the scheduling of price-taker hybrid companies

The Effect of DA-RTP Programs on Price-Maker Companies

This problem for price-maker companies is more complicated, because their strategy would affect the market price significantly. Here, instead of forecasting the market price, rivals' bids and offers should be predicted and based on that the optimum participation strategy can be evaluated [60]. This procedure leads to a bilevel optimization problem. In the first level the company's profit is maximized, and in the second level the market clearing process is simulated.

In addition to the previously mentioned advantage of DA-RTP programs, i.e., reduction of the associated risk of forecasted parameters, it can also be useful in removing line congestion. Transmission-line congestion may result in different nodal prices. In its extreme, the system operates in islanding mode, electrically not physically. This extreme situation can lead to a very high price in the created island. Therefore, the congestion may increase the cost of feeding contracted demands in the retail side. DA-RTP programs are strong feedbacks that can remove congestions. If the price is increased due to the line congestion, this would be reflected to the demand side by DA-RTP programs. By this feedback, the affected loads will reduce their consumption and the congestion can be removed.

Market Strategies of Demand Response Players (DR Aggregator, Electricity Retailer, Wind Power Producer)

DR programs were firstly proposed with the aim of mitigating the deficiencies of the systems. However, nowadays, these programs are considered as virtual resources, due to their high potential in power system studies [66, 67].

Demand response (DR) has been widely developed in electricity markets, where a great deal of attention has been paid on how to model various load management programs for electricity consumers. The recent challenges in electricity markets, however, urge the need for active involvements of DR in wholesale electricity markets, which indeed introduces DR aggregators as new entities in markets. DR aggregators mainly act as an intermediary between consumers and wholesale markets. These players are able to trade their DR either directly into the market or through other market players [68].

Among market players, electricity retailers would utilize DR to avoid facing with market price spikes, and thus to increase their profit. A real-time DR is proposed in [69], through which retailers procure their energy through real-time DR besides their traditional resources, i.e., pool markets and long-term contracts. A stochastic programming approach is formulated in which pool prices and consumers' behavior are associated with uncertainty. The given model, thus, gives retailers an option to determine their share from the given traditional and DR resources according to their ability to take risk, which is modeled through conditional value at risk (CVaR).

Another DR model is presented in [70], where electricity retailers are given an opportunity to procure their DR through long-term bilateral contracts to short-term DR. Various DR contracts such as forward DR and DR options are developed. Retailers buy forward DR at a fixed price and volume for a specific period, which obliged them to execute the contract in real time. DR options, however, give some level of flexibility to retailers through which they can decide not to apply the agreed contract in real time if they see it unnecessary, given that they pay a predefined penalty to DR providers. As for short-term DR, a reward-based DR program is formulated in which consumers' participation in this program is considered uncertain. The overall problem is formulated in a two-stage stochastic model whose feasibility is evaluated on a realistic case of the Australian National Electricity Market (NEM). Figure 10.12 illustrates the overall model for electricity retailers considering their options to employ demand response to meet their demand.

Arasteh et al. [71] addressed the policy of a retailer to participate in electricity and demand response exchange (DRX) markets with the aim of maximizing the expected profit. The presented decision-making framework includes the elastic response of end users regarding the electricity prices. Figure 10.13 shows the presented framework. It should be noted that DRX is a market-based concept to trade DR that has been introduced in [72]. DRX requires an operator to collect DR

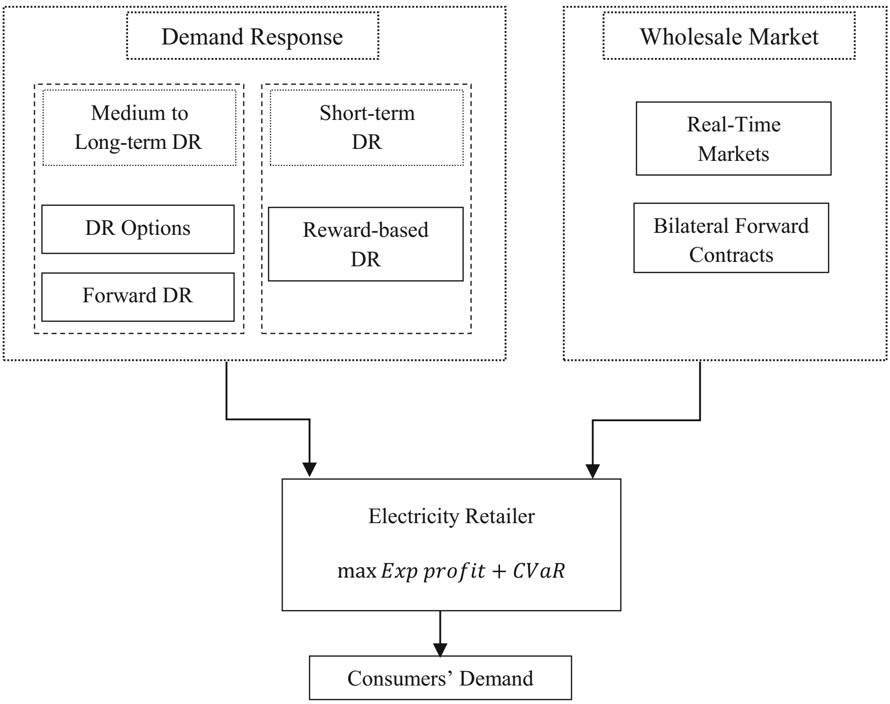

Fig. 10.12 Demand response for electricity retailers

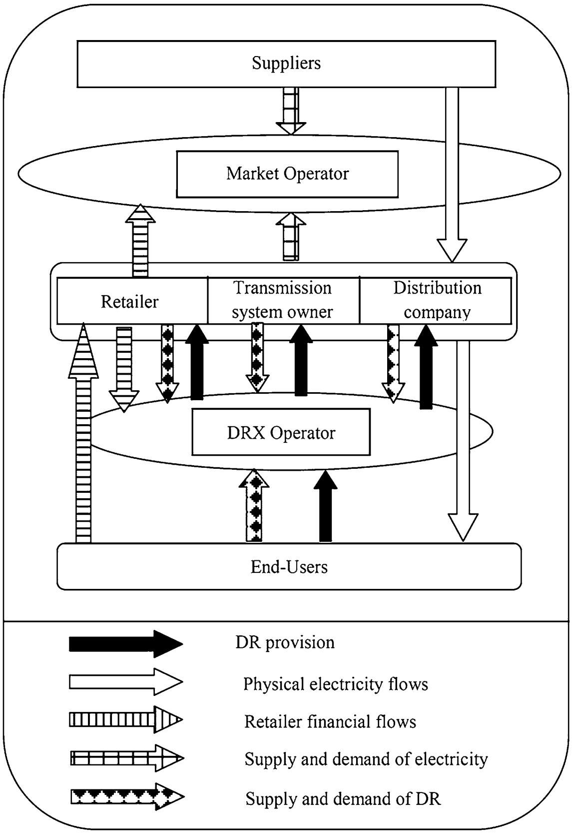

Fig. 10.13 The retailer framework to participate in electricity and DR markets [71]

offers/bids to clear the market and determine the equilibrium point [72, 73]. In [73], suitable methods have been proposed for DR buyers and sellers to participate in the DRX market.

A wind power producer is another market player that is interested to employ demand response. As wind power penetration in electricity markets increases, it is expected that these producers are treated as similar to existing generators in that they are responsible for any real-time mismatch between their offer and actual production. As a result, they can either compensate for their mismatch in real-time markets or utilize DR for this purpose. A bidding strategy by wind power producers is proposed in [74], where these producers can have a set of DR agreements with DR aggregators with which they traded their energy. Besides forward DR agreements and DR options, a new DR contract is developed in which although the contract is set with a given price and DR volume, in real time, a wind power producer can distribute the contracted volume over the given period in order to better manage its mismatch. That is, during the time a flexible DR contract is set, only total DR volume is agreed for a specific period. However, in the delivery time, the wind power producer is able to use this volume over the given period according to its requirement. The proposed problem is formulated in a two-step model in which the wind power producer seeks to maximize its profit through offering in the market while utilizing the given DR agreements. The feasibility of the given model is then evaluated on the Australian National Electricity Market (NEM) [74] and the Nordic market [75] according to their specific features. While the Australian NEM is cleared as a single-settlement market, the Nordic market comprises spot and balancing markets, which are cleared on the day-ahead basis and in real time, respectively.

DR aggregators are able to trade their DR with various DR purchasers as well as in the wholesale market. DR aggregator's behavior is modeled in wind power offering in [76]. A game theoretical model is proposed in which a wind power producer needs to buy DR from a DR aggregator while considering its rival competitors. A bilevel problem is mathematically formulated in which the wind power producer maximizes its profit in the upper level, while the lower level problem addresses the DR aggregator's profit maximization model. That is, the wind power producer sells its energy in the market while trading with the DR aggregator. The DR volume depends on how competitive the wind power producer is compared to other options that the DR aggregator has to trade its DR. This is indeed determined in the lower level, where the DR aggregator has to maximize its profit through trading its DR with other purchases, the given wind power producer, and the wholesale market. The proposed bilevel problem is then transformed into a single-level linear problem to be solvable using commercially available tools. The paper is then studied on a case study, where the proposed model is evaluated using several illustrative cases.

At high level of wind power penetration, some wind power producers might act strategically to affect the market. They will use their market power to increase their profit by altering the market clearing price. On the other hand, these producers may employ demand response to manage their market power by coping with their power production variability and uncertainty. To this end, a bilevel model with a single upper level, i.e., a wind power producer, and two lower level problems, i.e., market clearing and DR aggregator profit function, are formulated [77]. The wind power producer aims at maximizing its profit while affecting the market price, determined in lower level problem 1, and procuring DR from the DR aggregator in lower level problem 2. A risk-constrained stochastic model is proposed for the wind power producer through which the share of day-ahead and balancing markets as well as DR volume are determined, while the day-ahead offer and DR price are fed to lower level problems 1 and 2, respectively. As a result of these decisions, the market price as well as the acquired DR volume are determined in their corresponding lower level models. The problem is transformed into a single-level problem by replacing the lower level problems with their KKT conditions. Further, using proper techniques, the equivalent single-level problem is linearized and then solved using the CPLEX solver under GAMS. A case of the Nordic market is used to assess the proposed model, where the impact of DR on the strategic behavior of the wind power producer is addressed. There are several distributed algorithms that have the capability of solving large-scale power system problems in an efficient manner, such as the proposed method in [78, 79].

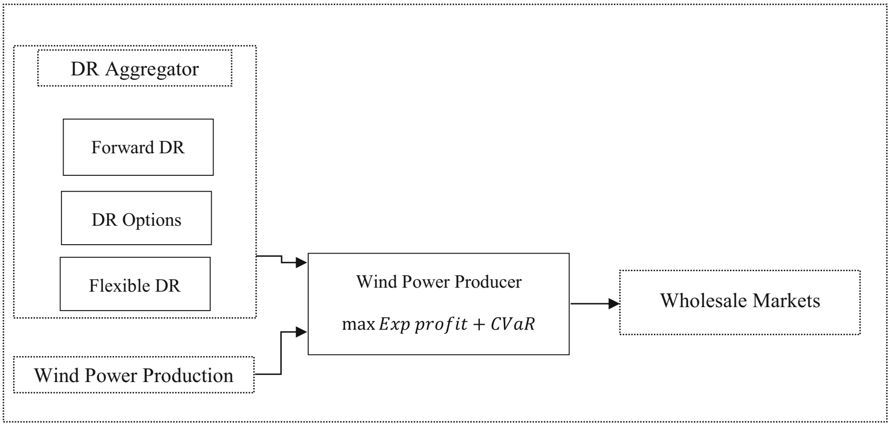

Fig. 10.14 Demand response for wind power producers

Figure 10.14 provides DR applications by wind power producers.

Recent Studies on Demand Response

Demand response allows management of energy loads by addressing objectives such as cost savings and peak load reduction [80]. The DR management strategy requires algorithms for addressing such objectives like economic dispatch [81]. Researchers in [82] utilized a multi-objective strategy for solving the DR objective. Rabiee et al. [83] proposed a new methodology for control of power systems through voltage correction. The strategy minimizes control costs by maintaining a desired load margin (LM). However these algorithms require enforcement of practical constraints for utilities and market price. Darby [84] set up the background issues behind the implementation of storage heating systems in DR frameworks. Ghavidel et al. [85] proposed a self-scheduled framework for demand response which considers consumer and electricity market price uncertainties. In [86] a solution to these issues was proposed by designing a short-term design strategy based on an electrical retailer point of view. In [87] a new short-term DR strategy was devised which takes into account consumer behavior. Researchers in [88] used distributed techniques to assist demand response integration in serving the needs of the customer. In [89] an optimal probabilistic scheduling model is used to determine demand response. The strategy has been proved to be optimal which minimizes total cost of the hub. In [90] the demand response applications are integrated in renewable energy frameworks. The strategy has been proved to adapt to the dynamics of the renewable generation and energy storage in the network. In [91] a real-time low-complexity demand response module was designed for thermostatically controlled loads. The proposed scheme was considered to be adaptive to changes in renewable generation. In [92, 93], a demand response-enabled distribution system was designed. The system can tackle noisy inputs and is capable of accurate state estimation. Researchers in [94] devised an algorithm to mapping the demand response problem with energy flow in renewable energy-based heating systems. Srivastava et al. [95] devised regression models for demand response predictions and determined that these models are highly functional in urbanized areas. Crosbie et al. [96] assessed demand response for applications in buildings. Viana et al. [97] analyzed demand response for a renewable distributed generation system. Their framework proved to be an important resource for power utility planning. Thornton et al. [98] followed the Internet of Things approach to studying the demand response in a distributed manner. The hardware-in-loop system proved to be scalable for integration in real-time systems. In [99] a Stackelberg game-based approach was used for demand response calculations for vehicle charging. The approach proved to be quite effective for multiple utility environments. Motalleb et al. [100] considered dynamic programming for calculating demand response while scheduling storage loads. The strategy minimized demand-side electricity cost throughout the period of simulation.

Conclusion

This chapter reviewed the demand response programs (DRPs) as one of the key features and components of the smart grids. DRPs are essential to cope with the upcoming challenges of the future systems and lead the operation and development of the systems in a sustainable manner. Therefore, we provided a comprehensive survey on the state of the art and the future trends of the DRPs. Although DRPs were firstly introduced with the aim of mitigating the system deficiencies (such as reliability problems and price spikes), currently they are considered as the virtual resources due to their beneficial potential. In this regard, the methods to model these programs are introduced in this chapter. In addition to the investigation of the available and novel models, the integration of DR programs with other models in power system studies is investigated. Furthermore, the participation strategies of market players in electricity and DR markets are addressed and the decision-making frameworks are explained. All the investigation results express the benefit of the DR implementation in various domains of power system.

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References

1. Parvania, M., & FotuhiFioruzabad, M. (2010). Demand response scheduling by stochastic SCUC. *IEEE Transactions on Smart Grid, 1*, 89–98.
2. Crossley, D. (2006). *Worldwide survey of network-driven demand-side management projects* (1st ed.). Paris: IEA Press.
3. Arasteh, H., SadeghSepasian, M., & Vahidinasab, V. (2015). Toward a smart distribution system expansion planning by considering demand response resources. *Journal of Operation and Automation in Power Engineering (JOAPE), 3*(2), 116–130.
4. Bompard, E., Ma, Y., Napoli, R., & Abrate, G. (2007). The demand elasticity impacts on the strategic bidding behavior of the electricity producers. *IEEE Transactions on Power Systems., 22*(1), 188–197.
5. Goel, L., Wu, Q., & Wang, P. (2007). Reliability enhancement and nodal price volatility reduction of restructured power systems with stochastic demand side load shift. *IEEE Power Engineering Society General Meeting Conference* (pp. 1–8).
6. Yu, N., & Yu, J. L. (2006). Optimal TOU decision considering demand response model. *International Conference on Power System Technology* (pp. 1–5).
7. Goel, L., Qiuwei, W., & Peng, W. (2006). Reliability enhancement of a deregulated power system considering demand response. *IEEE Power Engineering Society General Meeting Conference* (pp. 1–6).
8. Su, C. L., & Kirschen, D. (2009). Quantifying the effect of demand response on electricity markets. *IEEE Transactions on Power Systems., 24*(3), 1199–1207.
9. Schweppe, F. C., Caramanis, M. C., Tabors, R. D., & Bohn, R. E. (2013). *Spot pricing of electricity*. Berlin: Springer Science & Business Media.
10. Yousefi, S., Moghaddam, M. P., & Majd, V. J. (2011). Optimal real time pricing in an agent-based retail market using a comprehensive demand response model. *Energy, 36*(9), 5716–5727.
11. Conejo, A. J., Morales, M., & Baringo, L. (2010). Real-time demand response model. *IEEE Transactions on Smart Grid, 1*(3), 236–242.
12. Mahmoudi-Kohan, N., Parsa Moghaddam, M., & Sheikh-El-Eslami, M. K. (2010). An annual framework for clustering-based pricing for an electricity retailer. *Electric Power Systems Research, 80*(9), 1042–1048.
13. Hatami, A. R., Seifi, H., & Sheikh-El-Eslami, M. K. (2009). Optimal selling price and energy procurement strategies for a retailer in an electricity market. *Electric Power Systems Research, 79*(1), 246–254.
14. Alcázar-Ortega, M., Escrivá-Escrivá, G., & Segura-Heras, I. (2011). Methodology for validating technical tools to assess customer demand response: Application to a commercial customer. *Energy Conversion and Management, 52*(2), 1507–1511.
15. Chao, H. (2011). Demand response in wholesale electricity markets: The choice of customer baseline. *Journal of Regulatory Economics, 39*(1), 68–88.
16. Ferreira, R. S., Barroso, L. A., & Carvalho, M. M. (2012). Demand response models with correlated price data: A robust optimization approach. *Applied Energy, 96*, 133–149.
17. Lecocq, S., & Robin, M. (2006). Estimating demand response with panel data. *Empirical Economics, 31*(4), 1043–1060.
18. Chen, L., Li, N., Low, S. H., & Doyle, J. C. (2010). Two market models for demand response in power networks. *First IEEE International Conference on Smart Grid Communications* (pp. 397–402).
19. Kirschen, D. S., Strbac, G., Cumperayot, P., & DdP, M. (2000). Factoring the elasticity of demand in electricity prices. *IEEE Transactions on Power Systems, 15*(2), 612–617.
20. Khodaei, A., Shahidehpour, M., & Bahramirad, S. (2011). SCUC with hourly demand response considering intertemporal load characteristics. *IEEE Transactions on Smart Grid, 2*(3), 564–571.

21. Aghaei, J., & Alizadeh, M. I. (2014). Robust n-k contingency constrained unit commitment with ancillary service demand response program. *IET Generation, Transmission and Distribution, 8*(12), 1928–1936.
22. Abdollahi, A., Moghaddam, M. P., Rashidinejad, M., & Sheikh-el-Eslami, M. K. (2012). Investigation of economic and environmental-driven demand response measures incorporating UC. *IEEE Transactions on Smart Grid, 3*(1), 12–25.
23. Aalami, H., Yousefi, G. R., & Moghadam, M. P. (2008). A MADM-based support system for DR programs. *43rd International Universities Power Engineering Conference* (pp. 1–7).
24. Aalami, H., Yousefi, G. R., & Moghadam, M. P. (2008). Demand response model considering EDRP and TOU programs. *IEEE/PES Transmission and Distribution Conference and Exposition*, 1–6.
25. Aalami, H. A., Moghaddam, M. P., & Yousefi, G. R. (2010). Demand response modeling considering interruptible/curtailable loads and capacity market programs. *Applied Energy, 87*(1), 243–250.
26. Aalami, H. A., Moghaddam, M. P., & Yousefi, G. R. (2010). Modeling and prioritizing demand response programs in power markets. *Electric Power Systems Research, 80*(4), 426–435.
27. Hajebrahimi, A., Abdollahi, A., & Rashidinejad, M. (2017). Probabilistic multiobjective transmission expansion planning incorporating demand response resources and large-scale distant wind farms. *IEEE Systems Journal, 11*(2), 1170–1181.
28. Aghaei, J., Alizadeh, M. I., Abdollahi, A., & Barani, M. (2016). Allocation of demand response resources: Towards an effective contribution to power system voltage stability. *IET Generation, Transmission and Distribution, 10*(16), 4169–4177.
29. Mollahassani-pour, M., Abdollahi, A., & Rashidinejad, M. (2015). Investigation of market-based demand response impacts on security-constrained preventive maintenance scheduling. *IEEE Systems Journal, 9*(4), 1496–1506.
30. Mollahassani-Pour, M., Rashidinejad, M., Abdollahi, A., & Forghani, M. A. (2017). Demand response resources' allocation in security-constrained preventive maintenance scheduling via MODM method. *IEEE Systems Journal, 11*(2), 1196–1207.
31. Aghaei, J., & Alizadeh, M. I. (2013). Critical peak pricing with load control demand response program in unit commitment problem. *IET Generation, Transmission and Distribution, 7*(7), 681–690.
32. Arasteh, H. R., Moghaddam, M. P., Sheikh-El-Eslami, M. K., & Abdollahi, A. (2013). Integrating commercial demand response resources with unit commitment. *Electrical Power and Energy Systems, 51*, 153–161.
33. Moghaddam, M. P., Abdollahi, A., & Rashidinejad, M. (2011). Flexible demand response programs modeling in competitive electricity markets. *Applied Energy, 88*(9), 3257–3269.
34. Tabandeh, A., Abdollahi, A., & Rashidinejad, M. (2016). Reliability constrained congestion management with uncertain negawatt demand response firms considering repairable advanced metering infrastructures. *Energy, 104*(1), 1 213-228.
35. Amini, M. H., Nabi B., & Haghifam M.-R. (2013). Load management using multi-agent systems in smart distribution network. *Power and Energy Society General Meeting (PES), 2013 IEEE*. IEEE, 2013.
36. Amini, M. H., Frye, J., Ilić, M. D., & Karabasoglu, O. (2015, October). Smart residential energy scheduling utilizing two stage mixed integer linear programming. In *North American power symposium (NAPS)* (pp. 1–6).
37. Amini, M. H., Nabi, B., Moghaddam, M. P., & Mortazavi, S. A. (2012, May). Evaluating the effect of demand response programs and fuel cost on PHEV owners behavior, a mathematical approach. In *Smart grids (ICSG), 2nd Iranian conference on IEEE* (pp. 1–6).
38. Boroojeni, K. G., Amini, M. H., & Iyengar, S. S. (2017). *End-user data privacy. Smart grids: Security and privacy issues* (pp. 85–92). Berlin: Springer International Publishing.
39. Parvania, M., Fotuhi-Firuzabad, M., & Shahidehpour, M. (2014, November). ISO's optimal strategies for scheduling the hourly demand response in day-ahead markets. *IEEE Transactions on Power Apparatus and Systems, 29*(6), 2636–2645.

40. Parvania, M., Fotuhi-Firuzabad, M., & Shahidehpour, M. (2013, December). Optimal demand response aggregation in wholesale electricity markets. *IEEE Transactions on Smart Grid, 4*(4), 1957–1965.
41. Mahmoudi, N., Heydarian-Forushani, E., Shafie-khah, M., Saha, T. K., Golshan, M. E. H., & Siano, P. (2017, February). A bottom-up approach for demand response aggregators' participation in electricity markets. *Electric Power Systems Research, 143*, 121–129.
42. Nguyen, D. T., Nguyen, H. T., & Le, L. B. (2016, September). Dynamic pricing design for demand response integration in power distribution networks. *IEEE Transactions on Power Apparatus and Systems, 31*(5), 3457–3472.
43. Wu, H., Shahidehpour, M., & Khodayar, M. E. (2013, August). Hourly demand response in day-ahead scheduling considering generating unit ramping cost. *IEEE Transactions on Power Apparatus and Systems, 28*(3), 2446–2454.
44. Papavasiliou, A., & Oren, S. S. (2014, January). Large-scale integration of deferrable demand and renewable energy sources. *IEEE Transactions on Power Apparatus and Systems, 29*(1), 489–499.
45. Knudsen, J., Hansen, J., & Annaswamy, A. M. (2016, May). A dynamic market mechanism for the integration of renewables and demand response. *IEEE Transactions on Control Systems Technology, 24*(3), 940–955.
46. Shafie-khah, M., Heydarian-Forushani, E., Osório, G. J., Gil, F. A. S., Aghaei, J., Barani, M., & Catalão, J. P. S. (2016, November). Optimal behavior of electric vehicle parking lots as demand response aggregation agents. *IEEE Transactions on Smart Grid, 7*(6), 2654–2665.
47. Amini, M. H., Parsa Moghaddam, M., & Heydarian Forushani, E. (2013). Forecasting the PEV owner reaction to the electricity price based on the customer acceptance index. In *Smart Grid Conference (SGC)*. IEEE.
48. Shao, S., Pipattanasomporn, M., & Rahman, S. (2011). Demand response as a load shaping tool in an intelligent grid with electric vehicles. *IEEE Transactions on Smart Grid, 2*(4), 624–631.
49. Fan, Z. (2012). A distributed demand response algorithm and its application to PHEV charging in smart grids. *IEEE Transactions on Smart Grid, 3*(3), 1280–1290.
50. Tan, Z., Yang, P., & Nehorai, A. (2014). An optimal and distributed demand response strategy with electric vehicles in the smart grid. *IEEE Transactions on Smart Grid, 5*(2), 861–869.
51. Rassaei, F., Soh, W. S., & Chua, K. C. (2015). A statistical modelling and analysis of residential electric vehicles' charging demand in smart grids. *2015 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT)* (pp. 1–5).
52. Rassaei, F., Soh, W. S., & Chua, K. C. (2015, October). Demand response for residential electric vehicles with random usage patterns in smart grids. *IEEE Transactions on Sustainable Energy, 6*(4), 1367–1376.
53. Rassaei, F., Soh, W. S., & Chua, K. C. (2016). *Distributed scalable autonomous market-based demand response via residential plug-in electric vehicles in smart grids* (Vol. 9, p. 3281). IEEE Transactions on Smart Grid. https://doi.org/10.1109/TSG.2016.2629515.
54. Rassaei, F., Soh, W. S., & Chua, K. C. (2015). Joint shaping and altering the demand profile by residential plug-in electric vehicles for forward and spot markets in smart grids. *2015 IEEE Innovative Smart Grid Technologies - Asia (ISGT ASIA)* (pp. 1–6).
55. Rassaei, F., Soh, W. S., & Chua, K. C., & Modarresi, M. S. (2017). Environmentally-friendly demand response for residential plug-in electric vehicles. *2017 IEEE Texas Power and Energy Conference (TPEC)* (pp. 1–6).
56. Fei, W., Hanchen, X., Xu, T., Li, K., Shafie-khah, M., & Catalão, J. P. S. (2017). The values of market-based demand response on improving power system reliability under extreme circumstances. *Applied Energy*.
57. Talari, S., Yazdaninejad, M., & Haghifam, M.-R. (2015, April). Stochastic-based scheduling of the microgrid operation including wind turbines, photovoltaic cells, energy storages and responsive loads. *IET Generation Transmission and Distribution, 9*(12), 1498–1509.
58. Kazemi, M., Mohammadi-Ivatloo, B., & Ehsan, M. (2015). Risk-constrained strategic bidding of Gencos considering demand response. *IEEE Transactions on Power Apparatus and Systems, 30*(1), 376–384.

59. Kazemi, M., Mohammadi-Ivatloo, B., & Ehsan, M. (2014). Risk-based bidding of large electric utilities using information gap decision theory considering demand response. *Electric Power Systems Research, 114*, 86–92.
60. Kazemi, M., Zareipour, H., Ehsan, M., & Rosehart, W. D. (2016). A robust linear approach for offering strategy of a hybrid electric energy company. *IEEE Transactions on Power Systems, 32*, 1949–1959.
61. Kharrati, S., Kazemi, M., & Ehsan, M. (2016). Equilibria in the competitive retail electricity market considering uncertainty and risk management. *Energy, 106*, 315–328.
62. Kharrati, S., Kazemi, M., & Ehsan, M. (2015). Medium-term retailer's planning and participation strategy considering electricity market uncertainties. *International Transactions on Electrical Energy Systems, 26*(5), 920–933.
63. Kazemi, M., Mohammadi-Ivatloo, B., & Ehsan, M. (2013). IGDT based risk-constrained strategic bidding of Gencos considering bilateral contracts. In *2013 21st Iranian Conference on Electrical Engineering (ICEE)*. IEEE, 2013 (pp. 1–6).
64. Hatami, A., Seifi, H., & Sheikh-El-Eslami, M. K. (2011). A stochastic-based decision-making framework for an electricity retailer: Time-of-use pricing and electricity portfolio optimization. *IEEE Transactions on Power Systems, 26*(4), 1808–1816.
65. Kirschen, D. S. (2003). Demand-side view of electricity markets. *IEEE Transactions on Power Apparatus and Systems, 18*(2), 520–527.
66. Arasteh, H., Sepasian, M. S., Vahidinasab, V., & Siano, P. (2016, December). SoS-based multiobjective distribution system expansion planning. *Electric Power Systems Research (EPSR), 141*, 392–406.
67. Arasteh, H., Sepasian, M. S., & Vahidinasab, V. (2016, January 1). An aggregated model for coordinated planning and reconfiguration of electric distribution networks. *Energy, 94*, 786–798.
68. Mahmoudi, N. (2015). *New demand response and its applications for electricity markets*. PhD, School of ITEE, University of Queensland, University of Queensland.
69. Mahmoudi, N., Eghbal, M., & Saha, T. K. (2014). Employing demand response in energy procurement plans of electricity retailers. *International Journal of Electrical Power & Energy Systems, 63*, 455–460.
70. Mahmoudi, N., Saha, T. K., & Eghbal, M. (2014). A new demand response scheme for electricity retailers. *Electric Power Systems Research, 108*, 144–152.
71. Arasteh, H. R., Parsa Moghaddam, M., & Sheikh-El-Eslami, M. K. (2013, March). A comprehensive framework for retailer's financial policy. *Journal of Electrical Systems and Signals, 1*(1), 7–18.
72. Nguyen, D. T., Negnevitsky, M., & Groot, M. D. (2011). Pool-based demand response exchange—Concept and modeling. *IEEE Transactions on Power Apparatus and Systems, 26*, 1677–1685.
73. Arasteh, H. R., Parsa Moghaddam, M., & Sheikh-El-Eslami, M. K. (2012). Bidding strategy in demand response exchange market. *2nd Iranian Conference on Smart Grid, Tehran, Iran*, May 23–24, 2012.
74. Mahmoudi, N., Saha, T. K., & Eghbal, M. (2015). Wind offering strategy in the Australian National Electricity Market: A two-step plan considering demand response. *Electric Power Systems Research, 119*, 187–198.
75. Mahmoudi, N., Saha, T. K., & Eghbal, M. (2015). Wind power offering strategy in day-ahead markets: Employing demand response in a two-stage plan. *IEEE Transactions on Power Systems, 30*(4), 1888–1896.
76. Mahmoudi, N., Saha, T. K., & Eghbal, M. (2014, November 15). Modelling demand response aggregator behavior in wind power offering strategies. *Applied Energy, 133*, 347–355.
77. Mahmoudi, N., Saha, T. K., & Eghbal, M. (2016). Demand response application by strategic wind power producers. *IEEE Transactions on Power Systems, 31*(2), 1227–1237.
78. Bahrami, S., & Amini, M. H. (2018). A decentralized trading algorithm for an electricity market with generation uncertainty. *Applied Energy, 218*, 520–532.

79. Mohammadi, A., Mehrtash, M., & Kargarian, A. (2018). Diagonal quadratic approximation for decentralized collaborative TSO+DSO optimal power flow. *IEEE Transactions on Smart Grid*, 1. https://doi.org/10.1109/TSG.2018.2796034.
80. Siano, P. (2014). Demand response and smart grids—A survey. *Renewable and Sustainable Energy Reviews, 30*, 461–478.
81. Bhattacharjee, V., & Khan, I. (2018). A non-linear convex cost model for economic dispatch in microgrids. *Applied Energy, 222*, 637–648.
82. Behrens, D., Schoormann, T., & Knackstedt, R. (2018). Developing an algorithm to consider multiple demand response objectives. *Engineering, Technology and Applied Science Research, 8*(1), 2621–2626.
83. Rabiee, A., Masood Mohseni-Bonab, S., Parniani, M., & Kamwa, I. (2018). Optimal cost of voltage security control using voltage dependent load models in presence of demand response. *IEEE Transactions on Smart Grid*, 1–12.
84. Darby, S. J. (2018). Smart electric storage heating and potential for residential demand response. *Energy Efficiency, 11*(1), 67–77.
85. Vahid-Ghavidel, M., Mahmoudi, N., & Mohammadi-ivatloo, B. (2018). Self-scheduling of demand response aggregators in short-term markets based on information gap decision theory. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2017.2788890.
86. do Prado, J. C., & Qiao, W. (2018). A stochastic decision-making model for an electricity retailer with intermittent renewable energy and short-term demand response. *IEEE Transactions on Smart Grid*, 1–12.
87. Salah, F., Henríquez, R., Wenzel, G., Olivares, D., Negrete-Pincetic, M., & Weinhardt, C. (2018). Portfolio design of a demand response aggregator with satisficing consumers. *IEEE Transactions on Smart Grid*. https://doi.org/10.1109/TSG.2018.2799822.
88. Hurtado, L. A., Mocanu, E., Nguyen, P. H., Gibescu, M., & Kamphuis, R. I. G. (2018, January). Enabling cooperative behavior for building demand response based on extended joint action learning. *IEEE Transactions on Industrial Informatics, 14*(1), 127–136.
89. Alipour, M., Zare, K., & Abapour, M. (2018, January). MINLP probabilistic scheduling model for demand response programs integrated energy hubs. *IEEE Transactions on Industrial Informatics, 14*(1), 79–88.
90. Bitaraf, H., & Rahman, S. (2018, January). Reducing curtailed wind energy through energy storage and demand response. *IEEE Transactions on Sustainable Energy, 9*(1), 228–236.
91. Behboodi, S., Chassin, D. P., Djilali, N., & Crawford, C. (2018). Transactive control of fast-acting demand response based on thermostatic loads in real-time retail electricity markets. *Applied Energy, 210*, 1310–1320.
92. Lu, T., Wang, Z., Wang, J., Ai, Q., & Wang, C. A data-driven Stackelberg market strategy for demand response-enabled distribution systems. *IEEE Transactions on Smart Grid*.
93. Rahimi, F., & Ipakchi, A. (2010). Demand response as a market resource under the smart grid paradigm. *IEEE Transactions on Smart Grid, 1*(1), 82–88.
94. Massrur, H. R., Niknam, T., & Fotuhi-Firuzabad, M. (2018). Investigation of carrier demand response uncertainty on energy flow of renewable-based integrated electricity-gas-heat systems. *IEEE Transactions on Industrial Informatics*. https://doi.org/10.1109/TII.2018.2798820.
95. Srivastava, A., Van Passel, S., & Laes, E. (2018). Assessing the success of electricity demand response programs: A meta-analysis. *Energy Research and Social Science, 40*, 110–117.
96. Crosbie, T., Broderick, J., Short, M., Charlesworth, R., & Dawood, M. (2018). Demand response technology readiness levels for energy management in Blocks of buildings. *Buildings, 8*(2), 13.
97. Viana, M. S., Manassero, G., & Udaeta, M. E. M. (2018). Analysis of demand response and photovoltaic distributed generation as resources for power utility planning. *Applied Energy, 217*, 456–466.
98. Thornton, M., Motalleb, M., Smidt, H., Branigan, J., & Ghorbani, R. (2018). Demo abstract: Testbed for distributed demand response devices—internet of things. *Computer Science-Research and Development, 33*(1–2), 277–278.

99. Shinde, P., & Swarup, K. S. (2018, September). Stackelberg game-based demand response in multiple utility environments for electric vehicle charging. *IET Electrical Systems in Transportation, 8*(3), 167–174.
100. Motalleb, M., Branigan, J., & Ghorbani, R. (2018). Demand response market considering dynamic pricing. *Computer Science-Research and Development, 33*(1–2), 257–258.

Chapter 11
Impact of Strategic Behaviors of the Electricity Consumers on Power System Reliability

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Introduction

Overview: Over the past few decades, electricity markets have created competitive environments for the participation of different players. Electricity consumers (as end users in power systems) can behave strategically based on their purposes in the markets. Their behaviors induce more uncertainty into the power grid, due to their dynamic load demands. Hence, a power system operator faces more difficulties in maintaining an acceptable level of reliability and security in the system. On the other hand, the strategic behaviors of electricity consumers can be as a double-edged sword in the power grid. There is a group of consumers who are flexible and so can be interrupted at critical time periods and pursue their economic targets in the

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electricity markets. However, the second group is concerned with electricity demand being provided to them with the desired reliability level. Hence, the decisions of this group of electrical consumers are in conflict with their corresponding demand response programs. According to the above statement, this chapter aims at investigating the impact of strategic behavior of the electrical consumers on power system reliability. In this way, different agents of electricity markets are defined in this chapter which their behavior can impact the market-clearing problem. Energy and reserve are assumed as electricity commodities in this chapter. Thus, a two-stage, day-ahead and real-time, stochastic unit commitment problem is solved to clear energy and reserve simultaneously considering the uncertainty of wind power generations and conventional generation units which impacts the reliability of sustainable power systems.

According to the growing awareness about the environment and the demand for a reliable power grid, providing reliable renewable-based systems is a task of future smart grids [1, 2]. In recent years, the increased use of renewable energies such as wind power generation has caused some challenges in power systems mainly due to the variable and stochastic nature of these non-dispatchable energy sources [3, 4]. In connection to this, the extant literature has several related works which present new methods to solve economic dispatch, optimal power flow [5], unit commitment [6], and market-clearing [7] problems considering variability and uncertainty of power generation for such technologies. For instance, in [8], the optimal power flow problem is solved considering wind power uncertainty. The stochastic behavior of wind power generation is modeled by a Weibull probability density function. Besides, a heuristic optimization method which is called modified cuckoo search is used to solve the problem. In [9], the economic dispatch problem is solved considering high penetration of wind power generation in the integrated energy storage systems. In the model, wind power is defined as a dispatchable variable. Moreover, dynamic programming is used to solve unit commitment and economic dispatch problems. The impacts of renewable energies on power system are evaluated via a Monte Carlo simulation which accounts for the uncertainty of wind power generation in [10–12]. In [5], the renewable power producers are modeled in a multi-agent environment where the uncertainty of these renewable resources is considered by employing a two-stage stochastic framework.

The power system's reliability depends on various factors such as load capacity and customer base, maintenance, as well as age and types of equipment [13]. Providing suitable operating reserves is one of the main duties of power system operator as this allows maintaining the desired reliability level of the power system, which is subjected to high-level uncertainty and stochastic behavior of market agents [14]. Hence, in new approaches, the stochastic and dynamic models are defined to determine operating reserves according to the stochastic nature of wind energy in the power system. Recent studies in this research area can be divided into two groups. The first group focuses on the approaches that allow obtaining operating reserves based on wind power uncertainty, but they do not consider customer's choice of reliability [3, 4, 7–12, 15–23]. However, the second group presents algorithms to determine reserves considering the customer's reliability choices and assesses the economic concepts related to the operating reserves [14]. Indeed, the second group follows the necessity of considering the consumers' strategic behavior in future smart grids. In this regard many efforts have been carried out to show the role of consumers' behavior in different aspects of the future interdependent networks [24]. In this context, in [25], decentralized control of responsive consumers is discussed by using a multi-agent method. In addition to these methods that can improve the robustness and security of the future interdependent systems even if a failure occurs in other networks [26], demand-side management resources and flexible electric vehicle charging loads can highlight the role of consumers in the future smart grids [27]. On this basis, the role of customers is highlighted in [28, 29], and consequently a framework for determining the reserve is developed by taking the customers' reliability choices into account.

In [17], the energy and spinning reserve market-clearing problem is solved with the aim of minimizing total cost in the considered system and risk level considering wind power and electrical load. Spinning reserves are provided by generators and loads in the model presented in [17]. In [18], a security-constrained unit commitment problem is solved to determine the reserve level linked to transmission stress and increase the reliability of the power system. In [19], a method for determining zonal reserves is presented. This method considers the uncertainty of renewable energies. Authors in [19] present a probabilistic and heuristic optimization technique to solve a similar problem. In [20], operating reserves are determined through a combination of robust optimization and conditional value at risk, in order to consider wind power output uncertainty. In [21], a combined dispatch and multistage reserve policy optimization problem is solved by using a robust optimization, which models net load uncertainty by applying some decision rules. Such rules are based on forecasting errors in [21]. In [22], an improved interval method is used to solve the unit commitment problem considering network constraints and power output uncertainty of high penetration of wind farms in the power systems. Moreover, authors simulate several cases, where the unit commitment problem is solved using stochastic programming, robust optimization, interval, and improved interval methods. The performance of these simulations is assessed on the basis of computational burden and total operating costs. Based on the analysis results, authors highlight the importance of a stochastic unit commitment approach since it best models the uncertainty of wind power generation in the power system.

This chapter first introduces the different agents of the restructured power system. Then, electricity consumers are classified according to their strategic behaviors in the electricity markets. Hence, different examples of the impacts of the behavior and uncertainty of agents are described and evaluated in this chapter. The rest of the chapter is organized as follows. In section "Electricity Market Model," the electricity market model is presented and described in detail. Classes of customers are introduced in section "Classes of Customers." Section "Simulation Results" outlines the results of the conducted simulations. Finally, section "Conclusions" concludes this chapter.

Electricity Market Model

Power system restructuring has led to the appearance of different agents, and these agents have the freedom to participate in electricity markets (EMs). In this chapter, the EM model is presented and fully described. Also, details of the agents whose behaviors can impact the problem are included in this section. The EM model aims to solve a stochastic unit commitment (SUC) problem and clear energy and reserve simultaneously. The SUC model consists of two stages. In the first stage, the day-ahead market (DAM) is presented where the uncertainty of decision-making variables is not seen. However, in the second stage the real-time market (RTM) considers the uncertainty of the wind farms' power output and other traditional sources of uncertainty in the power grid.

Objective Function

In this section, the objective function of the market-clearing model and its constraints are represented.

$$\begin{aligned}
\mathrm{EC} &= \sum_{t=1}^{N_T} \mathrm{EC}_t \\
&= \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C_{it}^{\mathrm{SU}} + \sum_{t=1}^{N_T} d_t \left[\sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \lambda_{itm}^{G}.p_{itm}^{G} - \sum_{j=1}^{N_L} \lambda_{jt}^{L}.L_{jt}^{S} + \sum_{k=1}^{N_W} \lambda^{\mathrm{WP}}{}_{kt}.P_{kt}^{S,\mathrm{WP}} \right] \\
&+ \sum_{\omega=1}^{N_\Omega} \pi_\omega . \left\{ \sum_{t=1}^{N_T}\sum_{i=1}^{N_G} C^{A}{}_{it\omega} + \sum_{t=1}^{N_T} d_t \left[\sum_{i=1}^{N_G}\sum_{m=1}^{N_{Oit}} \left(C^{R^U}{}_{i}.r^{U}{}_{it\omega} + C^{R^D}{}_{i}.r^{D}{}_{it\omega} \right.\right.\right. \\
&\left. + C^{R^{NS}}{}_{i}.r^{NS}{}_{it\omega} \right) + \sum_{j=1}^{N_L} \left(C^{R^U}{}_{j}.r^{U}{}_{jt\omega} + C^{R^D}{}_{j}.r^{D}{}_{jt\omega} \right. \\
&\left.\left.\left. + \mathrm{VOLL}_{jt}.L_{jt\omega}^{\mathrm{shed}} \right) + \sum_{k=1}^{N_W} V^{S}{}_{t}.S_{kt\omega} \right] \right\}
\end{aligned} \tag{11.1}$$

In Eq. (11.1), the total expected cost (EC) of the day-ahead and real-time markets is defined as the objective function. The cost terms from the first to the second line represent the expected costs of DAM that consist of the start-up cost of units, energy cost of units, utility of electricity customers, and cost of energy produced by wind farms, respectively. The subsequent lines in Eq. (11.1) gather the expected cost corresponding to the RTM which includes the costs related to the changes in the start-up states of generating units in DAM and RTM, reserve costs related to the generation side and electricity customer side, and costs of load shedding and wind power spillage, respectively. As mentioned before, EM includes different agents with its corresponding aims and constraints. In the following, some of these agents are introduced on the basis of their limitations.

Generation Companies (GenCos)

A GenCo is one of the agents in the electricity market; it is in charge of producing electric power in the system. Generally, GenCos are called to the dispatchable electrical energy power plants. The key constraints of GenCos in the DAM and RTM are represented hereinafter:

DAM GenCos' Constraints

Equations (11.2a–11.2c) represent power generation limits of GenCos in the DAM. Likewise, the maximum and minimum limitations of GenCos' power scheduling are represented in Eq. (11.2a). Besides, Eq. (11.2b) enforces the constraints related to the GenCos' energy blocks. In addition, Eq. (11.2c) shows that the power scheduling of GenCos in each time period equals the sum of their energy blocks:

$$\underline{P}_i . u_{it} \leq P^S{}_{it} \leq \overline{P}_{\mathrm{i}} . u_{it}, \quad \forall i, \forall t \tag{11.2a}$$

$$0 \leq p^G_{itm} \leq \overline{p}^G_{itm}, \quad \forall m, \forall i, \forall t \tag{11.2b}$$

$$P^S{}_{it} = \sum_{m=1}^{N_{Oit}} p^G_{itm}, \quad \forall i, \forall t. \tag{11.2c}$$

Equations (11.2d–11.2f) refer to the list of constraints corresponding to the start-up cost of GenCos:

$$C^{\mathrm{SU}}_{it} \geq \lambda^{\mathrm{SU}}_{it} . \left(u_{it} - u_{i(t-1)}\right), \quad \forall i, \forall t > 1 \tag{11.2d}$$

$$C^{\mathrm{SU}}_{i(t=1)} \geq \lambda^{\mathrm{SU}}_{i(t=1)} . \left(u_{i(t=1)} - u_{i(0)}\right), \quad \forall i, t = 1 \tag{11.2e}$$

$$C^{\mathrm{SU}}_{it} \geq 0, \quad \forall i, \forall t. \tag{11.2f}$$

RTM GenCos' Constraints

The power generation limits of GenCos in the RTM are enforced by Eq. (11.3a):

$$\underline{P}_i.v_{it\omega} \leq P^G{}_{it\omega} \leq \overline{P}_{\mathrm{i}}.v_{it\omega}, \quad \forall i, \forall t, \forall \omega. \tag{11.3a}$$

Equation (11.3b) represents the relation among the allocated energy of GenCos in the DAM and RTM, and the operating reserves in the RTM. Additionally, the operating reserve constraints of GenCos in the RTM, as in Eqs. (11.3b–11.3h), need to be included in the model:

$$P^G{}_{it\omega} - P^S{}_{it} = r^U{}_{it\omega} + r^{NS}{}_{it\omega} - r^D{}_{it\omega}, \quad \forall i, \forall t, \forall \omega. \tag{11.3b}$$

$$0 \leq r^U{}_{it\omega} \leq \overline{R^U}_i.u_{it}, \quad \forall i, \forall t, \forall \omega. \tag{11.3c}$$

$$0 \leq r^D{}_{it\omega} \leq \overline{R^D}_i.u_{it}, \quad \forall i, \forall t, \forall \omega. \tag{11.3d}$$

$$0 \leq r^{\mathrm{NS}}{}_{it\omega} \leq \overline{R^{\mathrm{NS}}}_i.\left(1 - u_{it}\right), \quad \forall i, \forall t, \forall \omega. \tag{11.3e}$$

$$r^U{}_{it\omega} + r^{\mathrm{NS}}{}_{it\omega} - r^D{}_{it\omega} = \sum_{m=1}^{N_{Oit}} r^G_{itm\omega}, \quad \forall i, \forall t, \forall \omega. \tag{11.3f}$$

$$r^G_{itm\omega} \leq \overline{p}^G_{itm} - p^G_{itm}, \quad \forall i, \forall t, \forall \omega. \tag{11.3g}$$

$$r^G_{itm\omega} \geq -p^G_{itm}, \quad \forall m, \forall i, \forall t, \forall \omega. \tag{11.3h}$$

The constraints related to the start-up cost due to the new commitment states of GenCos in the RTM are modeled by Eqs. (11.3h–11.3k):

$$C^A{}_{it\omega} = C^{\mathrm{SU}}{}_{it\omega} - C^{\mathrm{SU}}{}_{it}, \quad \forall i, \forall t, \forall \omega. \tag{11.3h}$$

$$C^{\mathrm{SU}}{}_{it\omega} \geq \lambda^{\mathrm{SU}}_{it}.\left(v_{it\omega} - v_{i(t-1)\omega}\right), \quad \forall i, \forall t > 1, \forall \omega. \tag{11.3i}$$

$$C^{\mathrm{SU}}_{i(t=1)\omega} \geq \lambda^{\mathrm{SU}}_{i(t=1)}.\left(v_{i(t=1)\omega} - u_{i(0)}\right), \quad \forall i, t = 1 \tag{11.3j}$$

$$C^{\mathrm{SU}}{}_{it\omega} \geq 0, \quad \forall i, \forall t, \forall \omega. \tag{11.3k}$$

Wind Farms' Constraints

Wind farm is one of the agents in the EM which produces non-dispatchable electrical power. Hence, wind power generation is one of the decision-maker variables that induce uncertainty into the market-clearing problem. As mentioned before, the two-stage stochastic unit commitment problem aims to clear energy and reserve in the DAM and RTM. The uncertainty of wind power generation is not considered in the first stage. Hence, the constraint related to the scheduling of wind power generation in the DAM is represented by Eq. (11.4a). In the second stage, for instance, a constraint related to the economic and technical concerns of the wind farms may be the real-time spillage of the generated power. Equation (11.4b) represents the wind spillage constraint of the wind farm in the RTM:

$$\underline{P}_{kt}^{\mathrm{WP}} \leq P_{kt}^{S,\mathrm{WP}} \leq \overline{P}_{kt}^{\mathrm{WP}}, \quad \forall k, \forall t. \tag{11.4a}$$

$$0 \leq S_{kt\omega} \leq P^{\mathrm{WP}}{}_{kt\omega}, \quad \forall k, \forall t, \forall \omega. \tag{11.4b}$$

Customers' Constraints

Customers are another group of agents in the electricity market. In the electricity market, these agents have the freedom to behave strategically on the basis of their preferences and desires. Classes of customers consist of economic followers, reliability followers, and neutral. Equation (11.5) represents the load shedding constraint of the consumers in the RTM. Other equations related to customer classes are described in section "Classes of Customers":

$$0 \leq L_{jt\omega}^{\mathrm{shed}} \leq L^{C}{}_{jt\omega}, \quad \forall j, \forall t, \forall \omega. \tag{11.5}$$

Grid Operator's Constraints

A grid operator is an agent who controls and manages the interactions among various agents in the power grid. The principal role of grid operator is to balance the transacted electrical energy in each bus of the system. The equations below are associated with the constraints of the grid operator in the DAM and RTM. Equation (11.6a) represents the balancing equation among GenCos, wind farms, and electrical loads. According to Eq. (11.6a), line capacity limitations and losses are not considered in the DAM. Therefore, the DAM is cleared as a pool-based market without network constraints:

$$\sum_{i=1}^{N_G} P^{S}{}_{it} + \sum_{k=1}^{N_W} P_t^{S,\mathrm{WP}} = \sum_{i=1}^{N_L} L^{S}{}_{jt}, \forall t. \tag{11.6a}$$

However, all constraints related to the power flows are included in the RTM. Equation (11.6b) represents the power balance equation in the RTM considering line losses. Further network related constraints are presented in Eq. (11.6c). The physical transfer limits, i.e., related to the capacity of a transmission line are shown in Eq. (11.6d):

$$\sum_{i:(i,n)} P^{G}{}_{it\omega} - \sum_{j:(j,n)} \left(L^{C}{}_{jt\omega} - L^{\text{shed}}_{jt\omega} \right) + \sum_{k:(k,n)} \left(P^{\text{WP}}{}_{kt\omega} - S_{kt\omega} \right)$$
$$- \sum_{r:(n,r)} f_{t\omega(n,r)} = 0, \quad \forall n, \forall t, \forall \omega. \tag{11.6b}$$

$$f_{t\omega(n,r)} = B_{(n,r)}.\left(\delta_{t\omega n} - \delta_{t\omega r}\right), \quad \forall (n,r) \in \Lambda, \forall t, \forall \omega. \tag{11.6c}$$

$$-\overline{f}_{(n,r)} \leq f_{t\omega(n,r)} \leq \overline{f}_{(n,r)}, \quad \forall (n,r) \in \Lambda, \forall \text{t}, \forall \omega. \tag{11.6d}$$

Classes of Customers

Economic Followers

These customers are mainly concerned by their economic situations, and hence show some flexibility in their electrical consumption patterns and quantities. As a result, they play a key role by acting as interruptible loads. This is done by reducing/shifting their loads in some time periods and hence providing an upward and/or downward spinning reserve. It should be noted that economic-driven customers can also provide a downward spinning reserve by increasing their consumptions during periods specified by the system operator.

In return, these customers may receive money as a reward or incentive for their valuable flexibility provisions in the forms of interruptible loads. Besides, the operating reserve that is provided by customers can be different depending on the uncertainty of wind power generation, electrical load, or power grid in the system.

Equations (11.7a and 11.7b) represent constraints related to the upward and downward operating reserves of economic-follower customers. Also, Eq. (11.7c) relates the allocated electrical load in the DAM and RTM, and the downward and upward operating reserves. This way, if customers decrease their electrical consumptions, they act as GenCos which increase their generation. Hence, this decrement is called upward operating reserve from the customer side. On the other hand, customers provide a downward operating reserve when they increase their consumption at the specific periods of time:

$$0 \leq r^{U}{}_{jt\omega} \leq \overline{R^{U}}{}_{j}, \quad \forall j, \forall t, \forall \omega. \tag{11.7a}$$

$$0 \leq r^{D}{}_{jt\omega} \leq \overline{R^{D}}{}_{j}, \quad \forall j, \forall t, \forall \omega. \tag{11.7b}$$

$$L^{C}{}_{jt\omega} - L^{S}{}_{jt} = r^{D}{}_{jt\omega} - r^{U}{}_{jt\omega}, \quad \forall j, \forall t, \forall \omega. \tag{11.7c}$$

Reliability Followers

Getting electricity according to their desired reliability level is the main concern of these customers. Unlike economic followers who assist the system to provide the electrical demand of the power system, reliability followers force the system to supply their desired electrical load. It is clear that behavior of reliability followers increases the operating costs of the system. Hence, they are in charge of paying a portion of this imposed cost. Hence, customers declare their desired reliability according to the value of loss load (VOLL) that is seen in the last line of Eq. (11.1).

Neutral Customers

The group of customers whose behavior cannot have any impact on the operating cost and reliability of the system is called neutral. In other words, neutral customers neither provide any operating reserve nor ask for any reliability level that would force the system operator to provide more energy and reserve for the system.

Simulation Results

In this section, the market-clearing model is assessed using the modified 3-bus test system that is shown in Fig. 11.1. It should be noticed that only electrical loads connected at buses 2 and 3 of the system are considered in this case study. In other words, the load connected at bus 1 (i.e., L1) is neglected in this study. The data for the generators and the system are given in Tables 11.1 and 11.2. Line

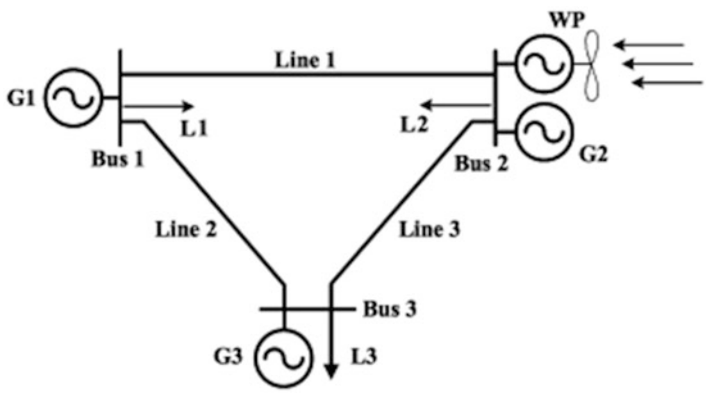

Fig. 11.1 A 3-bus test system [14, 30]

Table 11.1 Generator data for the 3-bus test system [14, 31]

	Unit 1	Unit 2	Unit 3
$\underline{P}_i$ (MW)	10	10	10
$\overline{P}_{\mathrm{i}}$ (MW)	100	100	50
$\lambda_{it}^{\mathrm{SU}}$ ($)	100	100	100
λ_{itm}^{G} ($/MWh)	30	40	20
$C^{R^U}{}_{it}$ ($/MWh)	5	7	8
$C^{R^D}{}_{it}$ ($/MWh)	5	7	8
$C^{R^{\mathrm{NS}}}{}_{it}$ ($/MWh)	4.5	5.5	7
Ramping capabilities (MW/h)	100	100	50
$\overline{R^U}_{it}$	90	90	40
$\overline{R^D}_{it}$	90	90	40
$\overline{R^{\mathrm{NS}}}_{it}$	100	100	50

Table 11.2 Other system data for the 3-bus test system [14, 31]

$C^{R^U}{}_{jt}$ ($/MWh)	70
$C^{R^D}{}_{jt}$ ($/MWh)	70
$\mathrm{VOLL}_{\mathrm{base}}$ ($/MWh)	1000
Lines reactance (p.u.)	0.13
Lines capacity (MW)	55
P_{base} (MW)	41
V_{base} (kV)	120

Table 11.3 Load scenarios at bus 3 and wind power in the 3-bus test system [14, 31]

Transmission lines	Capacity (MW)
Line (1,2)	10
Line (1,3)	28
Line (2,3)	24

capacity limits are provided in Table 11.3. Moreover, wind power generation and its scenarios and their corresponding probabilities are indicated in Tables 11.4 and 11.5, respectively. However, in some of the cases discussed here (specifically Cases 1 and 2), wind farm is not considered, and wind power generation uncertainty is ignored in Case 3 of this study. The power grid scenarios are generated using outage replacement rate (ORR) which equals 0.02 for generation units and is equal to 0.01 for transmission lines. Besides, the value of loss load (VOLL) of consumers is supposed to equal 1000 $/MWh. Different examples have been introduced in this section, in order to evaluate the impacts of customers' behavior and wind power

Table 11.4 Load scenarios at bus 3 and wind power in the 3-bus test system [14, 30, 31]

Period t	$P^{WP}{}_{t\omega}$ (MW) As forecasted	High	Low
1	6	9	2
2	20	30	13
3	35	50	25
4	8	12	6

Table 11.5 Probabilities of load scenarios at bus 3 and wind power in the 3-bus test system [14, 30, 31]

	$P^{WP}{}_{t\omega}$ (MW) As forecast	High	Low
Probability	0.6	0.2	0.2

Table 11.6 Day-ahead electrical demand of consumers and their expected load in the real-time market in Case 1

Consumer (MW)		Time (h) t 1	t 2	t 3	t 4
L2	$L^S{}_{jt}$	20	60	90	30
	$L^C{}_{jt}$	20	60	90	30
L3	$L^S{}_{jt}$	30	80	110	40
	$L^C{}_{jt}$	30	80	110	40

Table 11.7 Expected load shedding of consumers in Case 1

L_{jt}^{shed} (MW)	Time (h) t 1	t 2	t 3	t 4
L2	0	0	0.012	0
L3	0	0.123	13.367	0

uncertainty in the power system. Besides, the mixed-integer linear programming model has been implemented in GAMS 24.7.4 [32] that has been linked with MATLAB software [33].

Case 1

In this case, customers at nodes 2 and 3 are not economic followers. Hence, they do not provide upward and downward spinning reserves in the system. According to Eq. (11.7c), the real-time electrical demands of consumers 2 and 3 are equal to those of the day-ahead because their corresponding upward and downward spinning reserves are equal to zero. Table 11.6 shows the day-ahead electrical load of consumers and their expected real-time demand. Also, the expected load shedding of consumers is shown in Table 11.7. Moreover, power scheduling of GenCos in the day-ahead market and their expected real-time power generation are presented in Table 11.8. The difference between the dispatched power of GenCos in the DAM and the RTM is deployed as the operating reserves of GenCos in the RAM, as represented in Eq. (11.3b).

Table 11.8 Dispatched power of GenCos in the day-ahead market and their expected real-time power generation in Case 1

GenCo (MW)		Time (h) t 1	t 2	t 3	t 4
G1	P^S_{it}	0	30	50	10
	P^G_{it}	0	29.968	36.92	10.199
G2	P^S_{it}	0	60	100	10
	P^G_{it}	0.1	60.107	100	10.199
G3	P^S_{it}	50	50	50	50
	P^G_{it}	49.9	49.801	49.701	49.602

Table 11.9 Expected allocated operating reserves of GenCos in Case 1

GenCo (MW)		Time (h) t 1	t 2	t 3	t 4
G1	r^U_{it}	0	**0.008**	0	0.199
	r^D_{it}	0	**0.04**	13.08	0
	r^{NS}_{it}	0	0	0	0
G2	r^U_{it}	0	0.107	0	0.199
	r^D_{it}	0	0	0	0
	r^{NS}_{it}	0.1	0	0	0
G3	r^U_{it}	0	0	0	0
	r^D_{it}	0	0	0	0
	r^{NS}_{it}	0	0	0	0

Table 11.10 Demand of consumers in the day-ahead market and their expected load in real-time market in Case 2

Consumer (MW)		Time (h) t 1	t 2	t 3	t 4
L2	L^S_{jt}	20	60	90	30
	L^C_{jt}	18	54	81.015	27.988
L3	L^S_{jt}	30	80	110	40
	L^C_{jt}	32	87.909	101.478	44

As it can be seen in Table 11.9, G1 provides both upward and downward spinning reserves in the second time period. At first, it seems that these results are not true because GenCos can only provide upward or downward spinning reserves. However, the results are expected reserves that are generated in different scenarios. This means that G1 produces only upward spinning reserve in one scenario, and it provides the downward spinning reserve in another one.

Case 2

In Case 2, customers can join the reserve market as economic followers in the electricity market. Hence, there is no doubt that if they provide upward and downward spinning reserves, their electrical demands in the DAM and RTM are different. Table 11.10 shows the electrical demand of consumers in the DAM

Table 11.11 Expected load shedding of consumers in Case 2

L_{jt}^{shed} (MW)	Time (h)			
	t 1	*t* 2	*t* 3	*t* 4
L2	0	0	0	0
L3	0	0.08	0.358	0

Table 11.12 Dispatched power of GenCos in the day-ahead market and their real-time expected power generation in Case 2

GenCo (MW)		Time (h)			
		t 1	*t* 2	*t* 3	*t* 4
G1	$P^S{}_{it}$	0	34	50	20
	$P^G{}_{it}$	0.063	33.944	32.433	12.991
G2	$P^S{}_{it}$	0	56	100	0
	$P^G{}_{it}$	0.039	58.084	100	10.195
G3	$P^S{}_{it}$	**50**	**50**	**50**	**50**
	$P^G{}_{it}$	**49.9**	**49.801**	**49.701**	**49.6**

Table 11.13 Expected allocated operating reserves of GenCos in Case 2

GenCo (MW)		Time (h)			
		t 1	*t* 2	*t* 3	*t* 4
G1	$r^U{}_{it}$	0	0	0	0.135
	$r^D{}_{it}$	0	0.056	17.567	7.944
	$r^{NS}{}_{it}$	0.063	0	0	0
G2	$r^U{}_{it}$	0	2.84	0	0
	$r^D{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0.039	0	0	10.195
G3	$r^U{}_{it}$	**0**	**0**	**0**	**0**
	$r^D{}_{it}$	**0**	**0**	**0**	**0**
	$r^{NS}{}_{it}$	**0**	**0**	**0**	**0**

Table 11.14 Expected allocated operating reserves of consumers in Case 2

Consumer (MW)		Time (h)			
		t 1	*t* 2	*t* 3	*t* 4
L2	$r^U{}_{jt}$	2	6	8.985	2.012
	$r^D{}_{jt}$	0	0	0	0
L3	$r^U{}_{jt}$	0	**0.044**	8.522	0
	$r^D{}_{jt}$	2.002	**7.952**	0	4

and RTM. Table 11.11 presents the expected load shedding. As shown in Tables 11.7 and 11.11, the expected load shedding in Case 2 is less than that of Case 1 because of the higher reliability level that is provided by economic followers. Additionally, power scheduling of GenCos in the DAM and the RTM is represented in Table 11.12. Operating reserves that are provided by GenCos and consumers are presented in Tables 11.13 and 11.14, respectively.

As summarized in Table 11.12, the amounts of dispatched power of G3 in the DAM and RTM are not the same. According to Eq. (11.3b), it seems that G3 should provide the operating reserves. However, G3 does not provide any operating reserve

Table 11.15 Expected costs (ECs) in Cases 1 and 2

	Example 1	Example 2
EC ($)	27371.713	13920.459

Table 11.16 Day-ahead demand of consumers and their real-time expected load in Case 3

Consumer (MW)		Time (h)			
		t 1	t 2	t 3	t 4
L2	$L^S{}_{jt}$	20	60	90	30
	$L^C{}_{jt}$	18	54	81.018	32.944
L3	$L^S{}_{jt}$	30	80	110	40
	$L^C{}_{jt}$	33	87.909	101.973	44

for the system as shown in Table 11.13. This is because of grid uncertainty. In other words, G3 is in a shutdown mode in some scenarios, so its expected power generated in the RTM is less than 50 MW. However, G3 generates 50 MW when it is ON. Moreover, L3 provides both upward and downward spinning reserves in the second time period, which has been explained in Case 1. Table 11.15 compares the expected cost of the system in Cases 1 and 2. As shown in this table, economic followers decrease the expected cost of the system due to their participation in the reserve market to provide the electrical demand of the system.

Case 3

The impact of wind power generation on the system is assessed in Case 3. It should be noted that wind power uncertainty is not considered in this case. In other words, it is assumed that wind power prediction is out of any error, and the probability of scenario "As forecast" is equal to 1, and probabilities of scenarios "high" and "low" are both equal to 0. Tables 11.16 and 11.17 present the electrical loads and expected load shedding, respectively. As shown in Tables 11.11 and 11.17, load shedding in Case 3 in the third time period is less than that of Case 2 because of the higher reliability level that is provided by the wind farm like a power producer agent without uncertainty. The dispatched power of the GenCos in the DAM and RTM is shown in Table 11.19. As shown in Tables 11.12 and 11.18, the total amount of GenCos' dispatched power in Case 3 is less than any of the previous cases (i.e., Cases 1 and 2) because the wind farm's offered energy cost is assumed to equal zero in the electricity market. Hence, the wind farm's power generation is first cleared in the electricity market, and it decreases the dispatched power of GenCos in the DAM and the RTM. Moreover, wind power generation uncertainty is disregarded. Therefore, operating reserves that are provided by GenCos and consumers in Case 3 are less than any of those provided in Cases 1 and 2 (see in Tables 11.19 and 11.20).

Table 11.17 Expected load shedding of consumers in Case 3

L_{jt}^{shed} (MW)	Time (h)			
	t 1	t 2	t 3	t 4
L2	0	0	0	0
L3	0	0.08	0.355	0

Table 11.18 Dispatched power of GenCos in the day-ahead market and their real-time expected power generation in Case 3

GenCo (MW)		Time (h)			
		t 1	t 2	t 3	t 4
G1	$P^S{}_{it}$	0	34	49	12
	$P^G{}_{it}$	0.063	33.944	31.935	12.191
G2	$P^S{}_{it}$	0	36	66	0
	$P^G{}_{it}$	0.027	38.084	66	10.151
G3	$P^S{}_{it}$	44	50	50	50
	$P^G{}_{it}$	44.91	49.801	49.701	49.602

Table 11.19 Expected allocated operating reserves of GenCos in Case 3

GenCo (MW)		Time (h)			
		t 1	t 2	t 3	t 4
G1	$r^U{}_{it}$	0	0	0	0.199
	$r^D{}_{it}$	0	0.056	17.065	0.008
	$r^{NS}{}_{it}$	0.063	0	0	0
G2	$r^U{}_{it}$	0	2.084	0	0
	$r^D{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0	0.027	0	10.151
G3	$r^U{}_{it}$	0.998	0	0	0
	$r^D{}_{it}$	0	0	0	0
	$r^{NS}{}_{it}$	0	0	0	0

Table 11.20 Expected allocated operating reserves of consumers in Case 3

Consumer (MW)		Time (h)			
		t 1	t 2	t 3	t 4
L2	$r^U{}_{jt}$	2	6	8.982	0.024
	$r^D{}_{jt}$	0	0	0	2.968
L3	$r^U{}_{jt}$	0	0.0244	8.072	0
	$r^D{}_{jt}$	3	7.952	0	4

Case 4

In this case, wind power generation uncertainty is considered. Therefore, the maximum amount of wind power that can be committed to the DAM is the forecasted amount of the wind farm. However, three scenarios are defined for wind power generation with their corresponding probabilities as seen in Tables 11.4 and 11.5. Tables 11.21 and 11.22 show the DAM and RTM electrical loads and expected load shedding, respectively. Likewise, the dispatched power of the GenCos in the DAM and the RTM is shown in Table 11.23. Also, the expected allocated reserves for GenCos and consumers are shown in Tables 11.24 and 11.25, respectively.

Table 11.21 Electrical demand of consumers in the day-ahead and real-time markets in Case 4

Consumer (MW)		Time (h)			
		t 1	t 2	t 3	t 4
L2	$L^S{}_{jt}$	20	60	90	30
	$L^C{}_{jt}$	18.399	55.59	81.014	32.349
L3	$L^S{}_{jt}$	30	80	110	40
	$L^C{}_{jt}$	33	87.909	101.973	44

Table 11.22 Expected load shedding of consumers in Example 4

L^{shed}_{jt} (MW)	Time (h)			
	t 1	t 2	t 3	t 4
L2	0	0	0	0
L3	0	0.08	0.355	0

Table 11.23 Day-ahead dispatched power of GenCos and their real-time expected power generation in Case 4

GenCo (MW)		Time (h)			
		t 1	t 2	t 3	t 4
G1	$P^S{}_{it}$	0	34	49	12
	$P^G{}_{it}$	0.063	33.944	31.935	12.191
G2	$P^S{}_{it}$	0	36	66	0
	$P^G{}_{it}$	0.027	39.074	67.996	8.156
G3	$P^S{}_{it}$	44	50	50	50
	$P^G{}_{it}$	45.509	49.801	49.701	49.602

Table 11.24 Expected allocated operating reserves of GenCos in Case 4

GenCo (MW)		Time (h)			
		t 1	t 2	t 3	t 4
G1	$r^U{}_{it}$	0	0	0	0.199
	$r^D{}_{it}$	0	0.056	17.065	0.008
	$r^{NS}{}_{it}$	0.063	0	0	0
G2	$r^U{}_{it}$	0	3.074	1.996	0
	$r^D{}_{it}$	0	0	0	0
	$r^{\text{NS}}{}_{it}$	0.027	0	0	8.156
G3	$r^U{}_{it}$	1.597	0	0	0
	$r^D{}_{it}$	0	0	0	0
	$r^{\text{NS}}{}_{it}$	0	0	0	0

Table 11.25 Expected allocation of operating reserves of consumers in Case 4

Consumer (MW)		Time (h)			
		t 1	t 2	t 3	t 4
L2	$r^U{}_{jt}$	1.601	4.807	8.986	0.025
	$r^D{}_{jt}$	0	0.398	0	2.375
L3	$r^U{}_{jt}$	0	0.044	8.027	0
	$r^D{}_{jt}$	3	7.952	0	4

Table 11.26 Expected costs (ECs) in Cases 3 and 4

	Example 3	Example 4
EC ($)	11228.733	11243.46

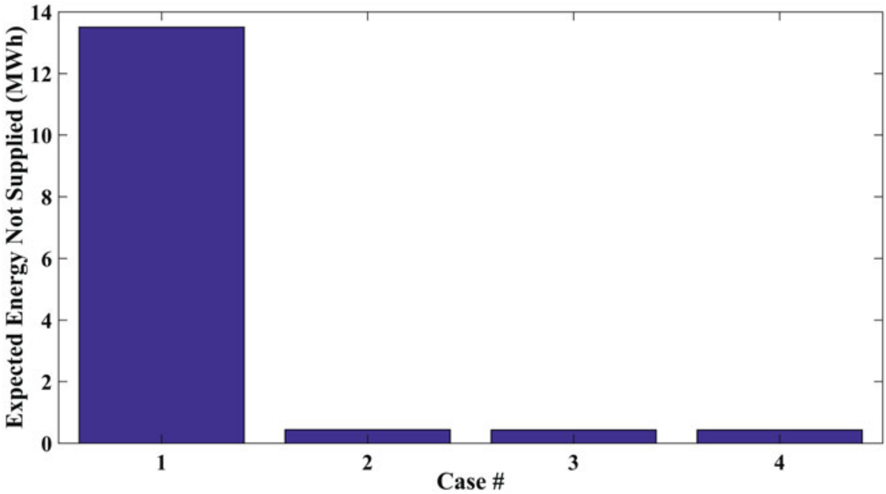

Fig. 11.2 Assessment of expected energy not supplied (EENS) in examples 1 to 4

As shown in Tables 11.19, 11.20, 11.24, and 11.25 wind power uncertainty has different impacts on the operating reserves that are provided by different agents in the electricity market. However, in Table 11.26, we can see that the expected cost in Case 4 is greater than that of Case 3. In other words, this study demonstrates that wind power uncertainty increases the system's expected cost. Figure 11.2 shows the impact of different examples on the reliability of the power system. In this chapter, expected energy not supplied (EENS) is chosen as reliability criteria of the system. As seen in Fig. 11.2, EENS in Case 2 is less than Case 1. In other words, joining consumers in the reserve market, as economic-follower agents, improves reliability level of the sustainable power systems. Also, considering wind farms in Cases 3 and 4 increases the reliability level of the system. Figure 11.3 demonstrates the impact of our studies on the total expected cost of the system. As shown in Fig. 11.3, economic followers decrease the expected cost of the system due to their flexible behavior of consumers to provide reserve and improve the sustainability of the power system. Moreover, the total expected cost of the system is minimum in Case 3 where wind farm is considered in the system, and we ignore uncertainty of wind power generation. However, the total expected cost in Case 4 is higher than in Case 3 due to the negative effect of wind power generation uncertainty. Furthermore, it should be noticed that the EM has been cleared based on a centralized approach in this chapter. Hence, energy management system has not developed as a multi-agent system (MAS). However, MASs could be one of the solutions for the sustainable power system to manage energy in a decentralized manner [34–36].

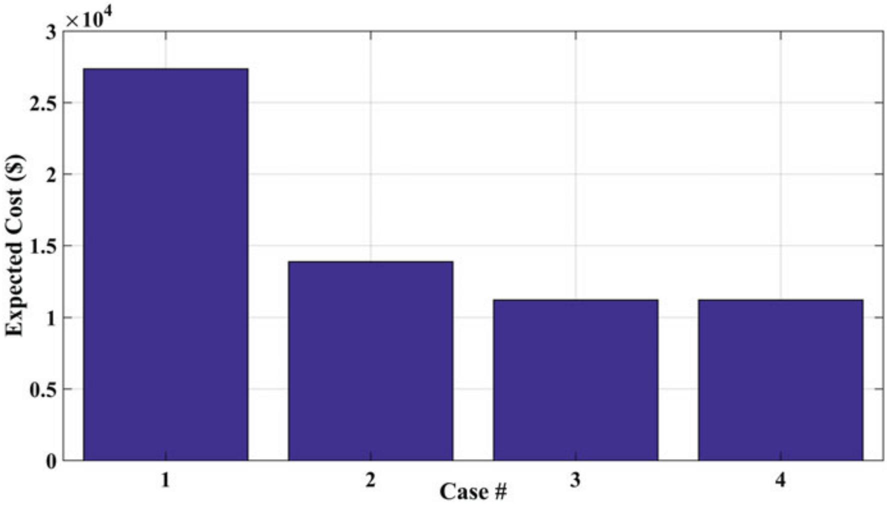

Fig. 11.3 Assessment of expected cost (EC) in examples 1 to 4

Conclusions

This chapter has introduced the agents of the restructured electricity market. The impacts of these agents' behavior on the power system have been assessed by setting up different cases. A two-stage stochastic unit commitment (SUC) model of a MILP nature is developed in this chapter, which is then solved to clear energy and reserve simultaneously. The day-ahead market (DAM) is presented in the first stage without the uncertainty of decision-making variables. However, the real-time market (RTM) is represented in the second stage considering the uncertainty of wind power generation and other traditional sources of uncertainty in the power grid. Moreover, electricity consumers have been classified into different groups of agents based on their strategic behaviors: economic followers, reliability followers, and neutral. Besides, examples of different cases have been studied to assess the influence of customer behavior and wind power uncertainty on the power system. Based on the analysis results in this chapter, key findings of this chapter are highlighted in the following:

- Economic followers improve the reliability level of the system and decrease load shedding.
- Economic-followers decrease the total expected cost of the system due to their flexible behavior to provide reserve and improve the sustainability of the power system.
- Considering wind farms in the power system optimizes the total expected cost of the system by reducing the total amount of GenCos' dispatched power.
- However, wind power uncertainty has a negative effect on the expected cost of the system.

Although different agents have been introduced in this chapter in the sustainable power systems, the market-clearing problem has been solved in centralized from. However, central energy management systems are not good strategies for forthcoming self-organized power systems. Therefore, decentralized electricity markets based on multi-agent energy management approach could be one of the solutions to increase energy efficiency and customers' choice of reliability in the sustainable power systems.

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Appendix 1: Nomenclature

Indices and Numbers

n	Index of system buses, from 1 to N_B.
i	Index of conventional generating units, from 1 to N_G.
j	Index of loads, from 1 to N_L.
t	Index of time periods, from 1 to N_T.
m	Index of energy blocks offered by conventional generating units, from 1 to N_{Oit}.
ω	Index of wind power, electrical load, and power grid scenarios, from 1 to Ω.

Continuous Variables

C_{it}^{SU}	Scheduled start-up cost ($).
${P^S}_{it}$	Power output of units in the DAM (MW).
p_{itm}^{G}	Power output from the m-th block of energy offered by the unit in DAM (MW).
${L^S}_{jt}$	Power consumed of load in DAM (MW).
${R^U}_{it}$	Up-spinning reserve in DAM (MW).
${R^D}_{it}$	Down-spinning reserve in DAM (MW).
${R^{NS}}_{it}$	Non-spinning reserve in DAM (MW).
${R^U}_{jt}$	Up-spinning reserve from demand side in DAM (MW).
${R^D}_{jt}$	Down-spinning reserve from demand side in DAM (MW).
$P_t^{S,\mathrm{WP}}$	Wind power in DAM (MW).
${C^A}_{it\omega}$	Start-up cost due to change in commitment status of units in DAM and RTM ($).
${P^G}_{it\omega}$	Power output of unit in RTM (MW).
${L^C}_{jt\omega}$	Electrical consumed in RTM (MW).
${r^U}_{it\omega}$	Up-spinning reserve in RTM (MW).
${r^D}_{it\omega}$	Down-spinning reserve in RTM (MW).
${r^{\mathrm{NS}}}_{it\omega}$	Non-spinning reserve in RTM (MW).
${r^U}_{jt\omega}$	Up-spinning reserve from demand side in RTM (MW).
${r^U}_{jt\omega}$	Down-spinning reserve from demand side in RTM (MW).
$r_{itm\omega}^{G}$	Reserve deployed from the m-th block of energy offered in RTM (MW).
$L_{jt\omega}^{\mathrm{shed}}$	Load shedding (MW).
$S_{t\omega}$	Wind power generation spillage (MW).
$f_{t\omega(n,r)}$	Power flow through line (n, r) (MW).
${P^{\mathrm{loss}}}_{t\omega(n,r)}$	Power loss in line (n, r) (MW).
$\delta_{t\omega n}$	Voltage angle at node.

Binary Variables

u_{it}	Commitment status of units in DAM.
$v_{it\omega}$	Commitment status of units in RTM.

Random Variables

$P^{\mathrm{WP}}{}_{t\omega}$	Wind power generation in RTM (MW).

Constants

d_t	Duration of time period (h).
$\lambda_{it}^{\mathrm{SU}}$	Start-up offer cost of unit ($).
λ_{itm}^{G}	Marginal cost of the m-th block of energy offered ($/MWh).
λ_{jt}^{L}	Utility of electrical load ($/MWh).
$\lambda^{\mathrm{WP}}{}_t$	Marginal cost of the energy offer submitted by the wind producer ($/MWh).
VOLL_{jt}	Value of loss load for load ($/MWh).
$V^S{}_t$	Wind spillage cost ($/MWh).
π_ω	Probability of scenarios.
$\overline{P}_{\mathrm{i}}$	Maximum capacity of units (MW).
$\underline{P}_i$	Minimum power output of generation units (MW).
$B_{(n,r)}$	Absolute value of the imaginary part of the admittance of line (n, r) (p.u.).
$\overline{f}_{(n,r)}$	Maximum capacity of line (n, r) (MW).

References

1. Amini, M. H., et al, (2013). Load management using multi-agent systems in smart distribution network. *IEEE Power and Energy Society General Meeting*.
2. Boroojeni, K. G., et al. (2017). Reliability in Smart Grids. In *Smart Grids: Security and privacy issues* (pp. 19–29). Cham: Springer.
3. Ahmadi-Khatir, A., Conejo, A. J., & Cherkaoui, R. (2013). Multi-area unit scheduling and reserve allocation under wind power uncertainty. *IEEE Transactions on power systems, 29*(4), 1701–1710.
4. Morales, J., Conejo, A., & Perez-Ruiz, J. (2009). Economic valuation of reserves in power systems with high penetration of wind power. *IEEE Transactions on Power Systems, 24*(2), 900–910.
5. Mohammadi, A., et al. (2018). Diagonal quadratic approximation for decentralized collaborative TSO+DSO optimal power flow. *IEEE Transactions on Smart Grid*, 1. https://doi.org/10.1109/TSG.2018.279603.
6. Shafie-khah, M., & Catalao, J. P. S. (2015). A stochastic multi-layer agent-based model to study electricity market participants behavior. *IEEE Transactions on Power Systems, 30*(2), 867–881.
7. Wang, F., Xu, H., Xu, T., Li, K., Shafie-Khah, M., & Catalao, J. P. (2017). The values of market-based demand response on improving power system reliability under extreme circumstances. *Applied Energy, 193*, 220–231.

8. Mishra, C., Singh, S. P., & Rokadia, J. (2015). Optimal power flow in the presence of wind power using modified cuckoo search. *IET Generation, Transmission & Distribution, 9*(7), 615–626.
9. Chen, H., Zhang, R., Li, G., Bai, L., & Li, F. (2016). Economic dispatch of wind integrated power systems with energy storage considering composite operating costs. *IET Generation, Transmission & Distribution, 10*(5), 1294–1303.
10. Silva, A. L., Sales, W., Manso, L., & Billinton, R. (2010). Long-term probabilistic evaluation of operating reserve requirements with renewable sources. *IEEE Transactions on Power Systems, 25*, 1.
11. Mastos, M., Lopes, J., Rosa, M., Ferreira, R., Silva, A., Sales, W., Resend, L., Manso, L., Cabral, P., Ferreira, M., Martins, N., Artiaz, C., Soto, F., & Lopez, R. (2009). Probabilistic evaluation of reserve requirements of generation systems with renewable power sources: The Portuguese and Spanish cases. *Electrical Power and Energy Systems, 31*, 562–569.
12. Leite da Silva, A. M., Rosa, M. A., Sales, W. S., & Matos, M. (2011). Long term evaluation of operating reserve with high penetration of renewable energy sources. *IEEE Conference, Power and Energy Society General Meeting*.
13. Sarwat, A. I., et al. (2016). Weather-based interruption prediction in the smart grid utilizing chronological data. *Journal of Modern Power Systems and Clean Energy, 4*(2), 308–315.
14. Shokri Gazafroudi, A., Afshar, K., & Bigdeli, N. (2015). Assessing the operating reserves and costs with considering customer choice and wind power uncertainty in pool-based power market. *International Journal of Electrical Power & Energy Systems, 67*, 202–215.
15. Ortega-Vazquez, M., & Kirschen, D. (2010). Assessing the impact of wind power generation on operating costs. *IEEE Transactions on Smart Grid, 1*, 3.
16. Ortega-Vazquez, M., & Kirschen, D. (2007). Optimizing the spinning reserve requirements using a cost/benefit analysis. *IEEE Transaction on Power Systems, 22*, 1.
17. Reddy, S. S., Bijwe, P. R., & Abhyankar, A. R. (2015). Joint energy and spinning reserve market clearing incorporating wind power and load forecast uncertainties. *IEEE Systems Journal, 9*, 1.
18. Lyon, J. D., Hedman, K. W., & Zhang, M. (2014). Reserve requirements to efficiently manage intra-zonal congestion. *IEEE Transactions on Power Systems, 29*, 1.
19. Wang, F., & Hedman, K. W. (2015). Dynamic reserve zones for day-ahead unit commitment with renewable resources. *IEEE Transactions on Power Systems, 30*, 2.
20. Wang, Z., Bian, Q., Xin, H., & Gan, D. (2016). A distributionally robust co-ordinated reserve scheduling model considering CVaR-based wind power reserve requirements. *IEEE Transactions on Sustainable Energy, 7*, 2.
21. Beuchat, P. N., Warrington, J., Summers, T. H., & Morari, M. (2016). Performance bounds for look-ahead power system dispatch using generalized multistage policies. *IEEE Transactions on Power Systems, 31*, 1.
22. Pandžić, H., Dvorkin, Y., Qiu, T., Wang, Y., & Kirschen, D. S. (2016). Toward cost-efficient and reliable unit commitment under uncertainty. *IEEE Transactions on Power Systems, 31*, 2.
23. Yousefi Ramandi, M., Afshar, K., Shokri Gazafroudi, A., & Bigdeli, N. (2016). Reliability and economic valuation of demand side management programming in wind integrated power systems. *International Journal of Electrical Power & Energy Systems, 78*, 258–268.
24. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks: From theory to application*. Cham: Springer.
25. Najafi, S., et al. (2018). Decentralized control of DR using a multi-agent method. In *Sustainable interdependent networks* (pp. 233–249). Cham: Springer.
26. Buldyrev, S. V., et al. (2010). Catastrophic cascade of failures in interdependent networks. *Nature, 464*(7291), 1025.
27. Amini, M. H., et al. (2018). *A panorama of future interdependent networks: From intelligent infrastructures to smart cities* (pp. 1–10). Cham: Sustainable Interdependent Networks. Springer.
28. Najafi, M., Ehsan, M., Fotuhi-Firuzabad, M., Akhavein, A., & Afshar, K. (2010). Optimal reserve capacity allocation with consideration of customer reliability requirements. *Energy, 35*, 3883–3890.

29. Ahmadi-Khatir, A., Fotuhi-Firuzabad, M., & Goel, L. (2009). Customer choice of reliability in spinning reserve procurement and cost allocation using well-being analysis. *Electric Power Systems Research, 79*, 1431–1440.
30. Shokri Gazafroudi, A., Shafie-khah, M., Abedi, M., Hosseinian, S. H., Dehkordi, G. H. R., Goel, L., Karimyan, P., Corchado, J. M., & Catalão, J. P. S. (July 2017). A novel stochastic reserve cost allocation approach of electricity market agents in the restructured power systems. *Electric Power Systems Research, 152*(C), 223–236.
31. Conejo, A. J., Carrion, M., & Morales, J. M. (2010). Decision making under uncertainty in electricity markets. In *International series in operations research & management science*. New York: Springer.
32. GAMS Release 2.50. (1999). *A user's guide*. GAMS Development Corporation. Retrieved September 20, 2017, from http://www.gams.com
33. The MathWorks. (2017). *MATLAB*. Retrieved September 20, 2017, from http://www.mathworks.com
34. Shokri Gazafroudi, A., Prieto-Castrillo, F., Pinto, T., & Corchado, J. M. (2017). Organization-based multi-agent system of local electricity market: Bottom-up approach. *15th International Conference on Practical Applications of Agents and Multi-Agent Systems (PAAMS)*.
35. Shokri Gazafroudi, A., Pinto, T., Prieto-Castrillo, F., Prieto, J., Corchado, J. M., Jozi, A., Vale, Z., & Venayagamoorthy, G. K. (2017). Organization-based multi-agent structure of the smart home electricity system. *IEEE Congress on Evolutionary Computation (CEC)*.
36. Shokri Gazafroudi, A., De Paz, J. F., Prieto-Castrillo, F., Villarrubia, G., Talari, S., Shafie-khah, M., & Catalão, J. P. S. A review of multi-agent based energy management systems. *8th International Symposium on Ambient Intelligence (ISAmI)*.

Chapter 12
A System of Systems Engineering Framework for Modern Power System Operation

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Nomenclature

a	Index for autonomous systems
b, b'	Border buses between two neighboring systems
i, j	Index for buses
k	Index for outer loop iterations
l	Index for levels in the hierarchical structure
m, n	Index for subproblems
q	Index for inner loop iterations
u	Index for generating units
Ω_i	Set of all buses connected to bus i
Ω_L^n	Set of all branches in system n
Ω_G^n	Set of all generating units located in system n
N_B^n	Number of buses in system n
d_i	Power demand at bus i
p_u	Power generated by unit u
PL_{ij}	Power flow in line ij
Θ	Bus voltage angles
$f_n(\cdot)$	Local objective function of system n
$f(p_u)$	Generation cost function of unit u
$f_{la}(\cdot)$	Local objective function of system a at level l
$g_n(\cdot)$	Compact form of inequality constraints of system n
$h_n(\cdot)$	Compact form of equality constraints of system n

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$g_{la}(\cdot)$ Set of local inequality constraints of system a at level l
$h_{la}(\cdot)$ Set of local equality constraints of system a at level l
θ_b Voltage angle of bus b
$\theta_{b,m}$ Voltage angle of bus b determined by system m
$\theta_{b,n}$ Voltage angle of bus b determined by system n
θ_{2a}^* Target values that are constants in microgrids' optimization
$\theta_{2a}'^*$ Response values that are constants in DSO's optimization
x_n Local variables of system n
$\tilde{x}_{la}$ Set of local variables of system a at level l
t_{2a} Target variables of system a at level 2
r_{2a} Response variables of system a at level 2
$\overline{P_u}$ Upper bound for generating unit u
$\underline{P_u}$ Lower bound for generating unit u

$\overline{PL_{ij}}$ Upper bound for power flow in line ij
$\underline{PL_{ij}}$ Lower bound for power flow in line ij

$\pi(\cdot)$ Penalty function
λ^T Lagrange multiplier
ω Penalty multiplier
β Step size

Introduction

Overview

In the literature, numerous definitions have been proposed for system of systems (SoS). The concept of system of systems has been widely used in defense applications. In addition, it has been applied to other domains, e.g., healthcare, robotics, global communication systems, transportation, space exploration, and power system operation.

In this chapter, we discuss about the possibility of modeling active distribution grids (ADGs), which are composed of several microgrids, based on the concept of system of systems. Although various energy management/control functions, such as long-term planning and day-ahead scheduling, can be investigated based on the concept of SoS, the main focus of this chapter is on the short-term ADG operation and the optimal power flow (OPF) problem. The whole ADG is considered to be an SoS in which distribution system operators (DSOs) and microgrids (MGs), which are autonomous entities, are modeled as self-governing systems. The information privacy of DSOs and MGs is explained, and a local OPF is formulated for each system taking into account the mutual interactions between DSOs and MGs. A distributed optimization algorithm, which is based on the augmented Lagrangian relaxation, is presented to find the optimal operating point of ADG while respecting information privacy of the subsystems. A test system is designed to provide a tutorial for readers on how to formulate local OPF problems of ADGs and MGs and how to implement the distributed optimization algorithm.

Modern Power Systems

Power systems, which are responsible for providing generation, transmission, and distribution of electrical energy, are among the most complex infrastructure in each society [1]. Conventionally, an electric power system consists of three major subsystems: generators that supply energy, transmission systems that transfer energy from power plants to load centers, and distribution systems that distribute electricity among end users [2]. However, emerging new technologies, deregulation rules and policies, and environmental issues have forced an ongoing transition from conventional power system structures toward intelligent and sustainable energy infrastructure [3, 4]. In these modernized systems, distributed generators (DGs), e.g., wind turbines and solar generations, are located in the distribution systems, which leads to the emergence of microgrids. Modern power systems have three important features:

- Emerging and participation of self-governing entities, each of which is responsible for a part of the system or a specific task.
- Energy and information flow among the self-governing entities are bidirectional.
- Each entity can have its own operating policies and rules.

These ongoing changes will increase power system complexity and bring new challenges in system planning, operation, and control problems. Figure 12.1 shows power system modernization.

Complexity and Challenges of Modern Power Systems

The complexity of conventional power systems is increasing by the modernization. System operators face new challenges due to such modernization. For instance, bidirectional energy flow causes problems for the protection relay coordination. Another example is penetration of renewable energy resources, such as wind turbines and solar generations, which brings new challenges for power system operators. Because of non-dispatchability of these energy resources, caused by geographical uncertainty and forecast errors, their scheduling and operation are more challenging compared to conventional generating units.

Power system deregulation leads to a competitive electricity market in which many autonomous entities act as market players. An independent system operator (ISO), which is not a market player, is needed to preserve the security and reliability of the whole system. Each market player, i.e., entity, has its policies and rules and aims at increasing its profit from the competitive market. Information and data of the entities are commercially sensitive and affect the entities' profit. Thus, the information privacy is an important issue in competitive electricity markets. The framework of the deregulated power systems can be mentioned in three stages:

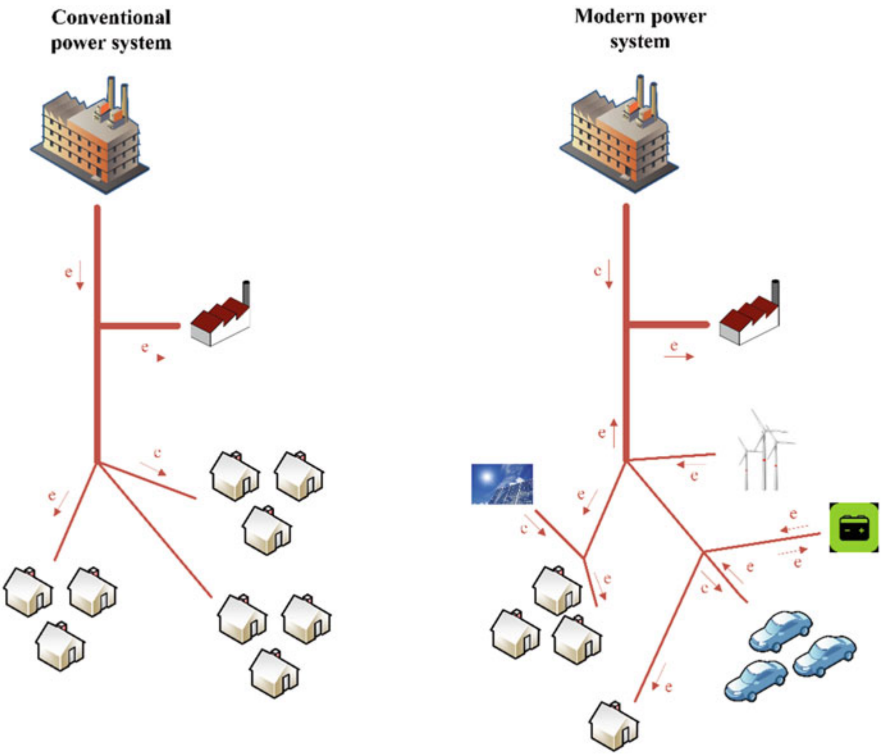

Fig. 12.1 Power system modernization

- Competition: The self-governing entities compete with each other to maximize their benefit.
- Information privacy: The entities are not willing to share their commercially sensitive data and information with other parties.
- Coordination: The entities need to be coordinated to satisfy reliability and security of the whole power system.

Assume two neighboring regions in a multiregional power system. Each region is governed by an autonomous entity. If the regions are isolated, they can be operated separately. However, if the regions are interconnected through tie lines, any decision made by an operator affects the decision made by another operator [5–7]. For instance, for an optimal power flow (OPF) problem, active and reactive power flow in a tile line affects voltage magnitudes and angles of the tie line ending terminals [8]. This, consequently, affects the OPF solution of each region. Thus, the regions' operators should cooperate to manage the whole system in a reliable and optimal manner. Therefore, coordinating OPF solutions of the regions is necessary. On the other hand, each entity is not willing to share its confidential information with another one. As a result, for solving the OPF problem without sharing information, it is necessary to have either a trustable third-party coordinator or a distributed management framework that does not need a third-party coordinator [5–7, 9, 10].

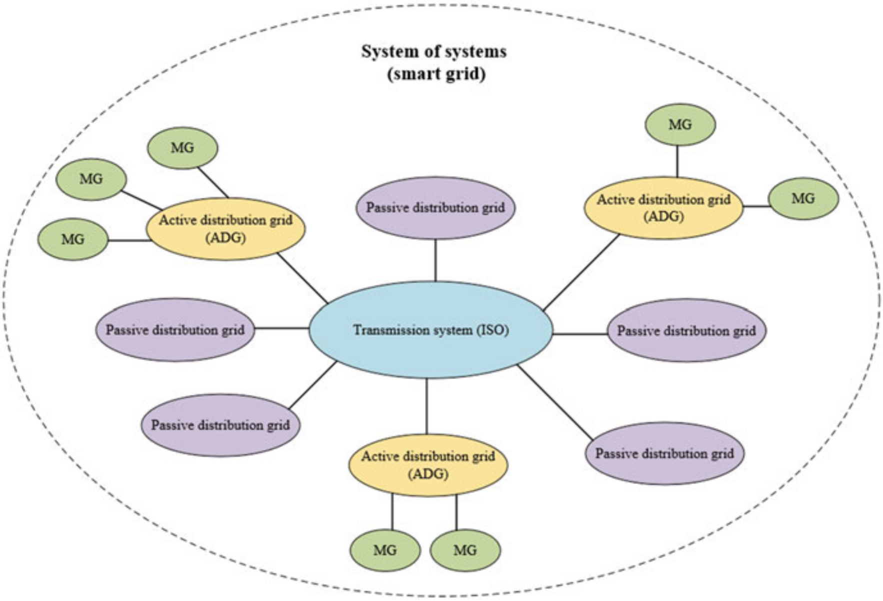

Fig. 12.2 A modern power system as a system of systems

System of Systems Engineering: A Solution for Modern Power System Challenges

In the literature, numerous definitions have been proposed for system of systems (SoS) [11–16]. As stated in [16], "Systems of Systems are large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal." The concept of system of systems engineering is potentially beneficial for modern power system planning, operation, and control. An SoS deals with the coordination of multiple subsystems, each of which has its privacy and rules, while the whole system follows a certain goal. Indeed, an SoS refers to a group of systems that are heterogeneous and independently operable with their local objectives, while they are linked together for realizing a secure and reliable operation of the entire SoS [16]. Modern power systems have a similar framework [17–19]. Figure 12.2 shows a power system with the framework of an SoS. In this framework, the transmission system, distribution systems, and microgrids are modeled as autonomous systems. These autonomous systems cooperate to ensure security and reliability of the whole SoS. While energy flows in a unidirectional manner from the transmission system toward passive distribution grids (distribution grids without DG units), bidirectional flow of energy and information exist between the transmission system and active distribution grids (distribution grids with DG units).

Recently, the application of system of systems engineering in power system operation and control problems has seen increased interest [8, 18, 20, 21]. An SoS framework is proposed in [8, 18] for the optimal operation of active distribution grids (ADGs). ADGs and microgrids are considered as autonomous systems. An optimization algorithm is formulated to solve OPF for the whole SoS while respecting the autonomy and privacy of each system. In [20], interactions between the transmission system and ADGs in a day-ahead electricity market are modeled based on the concept of SoS. A local day-ahead scheduling problem (see Ref. [21]) is formulated for each autonomous entity, and a distributed optimization algorithm is presented to coordinate the systems. Reference [22] is an extension of [20] that considers uncertainties of the renewable energy resources in the autonomous systems.

The application of system of systems engineering is also applied in other research areas. In [23], the author illustrated the importance of managing conflict and risk in a system of systems framework. In [24], the application of system of systems engineering is used to assess existing and new techniques of an agent system analysis to evaluate actual and theoretical attacks on multi-agent systems. An alternative method for a military system of systems, which required reliability, safety, availability, survivability, etc., is proposed in [25].

System of Systems-Based Optimal Power Flow in Active Distribution Grids

As explained in the previous section, the whole modern power system can be modeled based on an SoS framework. In this chapter, we focus on the modeling and operation of power distribution systems and mainly the optimal power flow (OPF) problem. The autonomous entities are the distribution system operator and microgrids.

Passive Distribution Grid

In conventional power systems, energy is generated in massive power plants and then transferred to load centers through transmission and distribution systems. Generating units are not located in the distribution systems near load centers. Such distribution systems are called passive systems and are modeled as a load from the perspective of transmission systems. The power flow is unidirectional, from the transmission system toward the passive distribution system. The cash flow (cost of energy) is also unidirectional, from the passive distribution system toward the transmission system. Figure 12.3 shows the energy and cash flow between a transmission system, a passive distribution grid, and a set of end users.

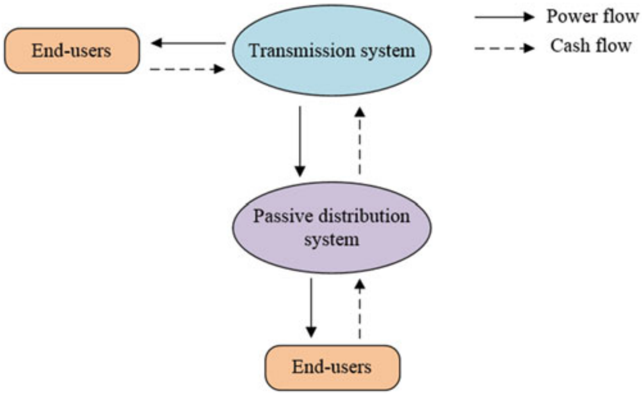

Fig. 12.3 Power flow and cash flow directions in passive distribution grids

An independent system operator (ISO) is in charge of the system scheduling. The passive distribution grids forecast their load and send it to ISO. The ISO gathers information from all loads and generating units and formulate a centralized optimization problem, for instance, for the short-term power system operation. This centralized optimization aims at maximizing the social welfare or minimizing costs subject to the system and generators' constraints [26–28].

Active Distribution Grid as a System of Systems

In response to environmental and technical issues, distributed generating units have been installed in power distribution grids [29–31]. DGs directly inject electricity into the distribution grid without requiring a transmission system. The electricity is distributed among end users through distribution feeders. Producing electricity near the load centers reduces the energy loss and enhances the power system efficiency. In modern power systems since instead of one entity many entities compete with each other, they prefer not to share all of their information, and this competition leads to reducing the electricity price in the market [32–34]. In addition, the reliability of such a distribution grid is higher than that of the passive distribution grid since an outage in the transmission system might not lead to the power outage in the distribution grid. To distinguish between modern distribution grids and conventional passive grids, we call the modern grids as active distribution grids (ADGs). The term "active" means that the distribution grid includes DG units, whereas the term "passive" refers to the distribution grids without any generating unit. As shown in Fig. 12.4, power flow and cash flow between the transmission and distribution systems are bidirectional, from the transmission to distribution and vice versa.

An active distribution grid is managed by a distribution system operator (DSO). DSO schedules the generation resources in ADG to minimize the operation cost

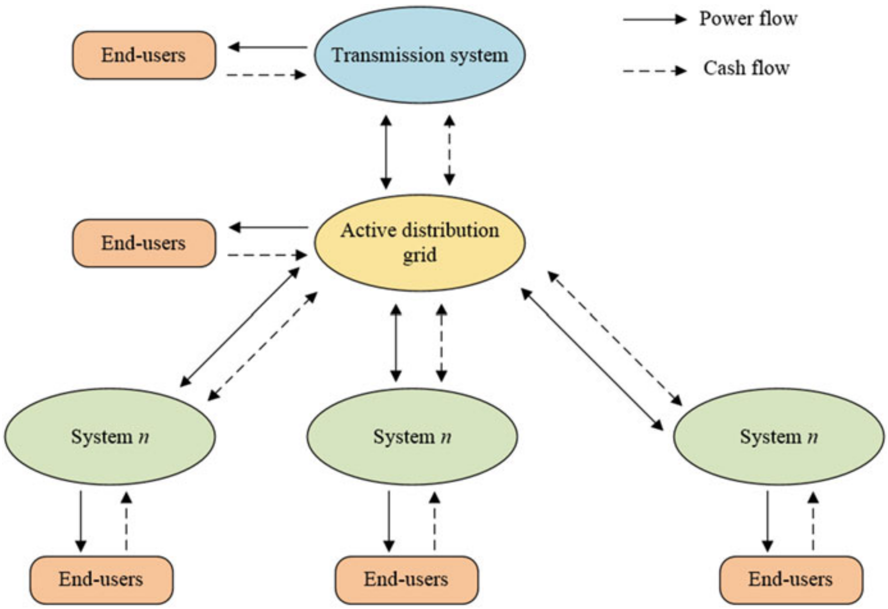

Fig. 12.4 Power flow and cash flow directions in active distribution networks

taking into account power balance and physical constraints of the distribution grid, such as line flow limits. On the other hand, ADG may consist of several microgrids (MGs). An MG is a low-voltage distribution network that includes a group of loads, distributed generation sources, and energy storage devices. In addition, an MG has an energy management system that monitors and controls DGs and loads [35–38]. The MG can work either in the grid-connected mode or islanded mode. When it is connected to the grid (i.e., to ADG), MG may act as either a load or a power source. One of the most important features of MGs is that they can work independently while being separated from the upstream grid [39–41]. This feature enhances the MG's reliability when a fault occurs in the upstream grid. MGs may cooperate with DSO to enhance the efficiency and performance of the entire active distribution grid. For instance, if an MG includes cheap generation resources while DSO's units are expensive, MG may sell power to DSO and reduce the total grid operating costs. Thus, as depicted in Fig. 12.4, power flow and cash flow are bidirectional, from DSO to MGs and vice versa.

MGs and DSO are independent systems with their own policies and rules. Each of these systems solves its local operation problem aiming at maximization of its benefit. Although these systems are independent and capable of working in the islanded mode, they are parts of a distribution grid that is more complex and capable of each MG and DSO. Thus, one can say that an active distribution system is an SoS in which MGs and DSO are autonomous systems.

A management framework is required to operate such an SoS-based distribution system. Deploying a centralized algorithm is not appropriate, as MGs and DSO are autonomous entities that are not willing to share their commercially sensitive information with other parties. This is not aligned with the concept of the electricity market. Indeed, sharing information may degrade the benefit that an entity may gain from the market. This may consequently discourage private sectors to invest in the distribution grid modernization. On the other hand, since MGs and DSO are parts of an interconnected SoS, their mutual interactions should be carefully modeled in the SoS operation. In other words, it is not appropriate to operate these systems in a completely separate manner. If we do not allow MGs and DSO to exchange energy, i.e., force them to work in the islanded mode, the distribution grid performance degrades, and the system reliability is in danger. On the other hand, if, for instance, MG1 and DSO are allowed to exchange energy, MG1 cannot ask to receive 100KW from DSO while DSO needs to receive 50 KW from MG1. This violates physical laws.

DSO and MGs know that they may benefit from a cooperative grid management framework. Thus, these systems may be willing to cooperate if they do not need to exchange their commercially sensitive information with other parties. The type and amount of the information that MGs and DSO should share depend on the considered energy management function, e.g., optimal power flow, state estimation, and optimal control. This chapter focuses on the OPF problem. In the following section, the OPF problems of MGs and DSO are formulated under two operating modes including islanded mode and integrated mode. The required information that needs to be shared between systems in an integrated OPF model is discussed.

Local OPF Problem of Autonomous Systems

AC optimal power flow is usually considered in the distribution system level. However, for the sake of simplicity and explanation, in this chapter, a DC-OPF problem is formulated for each autonomous system. Note that AC-OPF can easily replace DC-OPF without changing the SoS structure.

Islanded Mode

In the islanded mode,DSO and MGs are not connected. A local OPF is formulated for each autonomous system. Local OPFs are independent. In other words, any alteration in an MG does not affect DSO's operating point. Figure 12.5 shows two systems m and n that work in the islanded mode. The optimal power flow aims at finding the best possible power dispatch for DGs with the minimum cost to supply the demand. A compact form of OPF for system n is shown in Eq. (12.1):

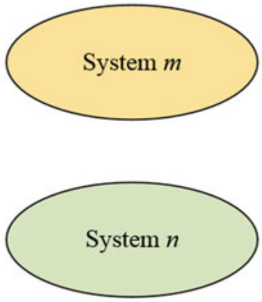

Fig. 12.5 Systems m and n working in the islanded mode

$$\min \quad f_n\left(x_n\right) \tag{12.1}$$

$$\text{s.t.}$$
$$h_n\left(x_n\right) = 0$$
$$g_n\left(x_n\right) \leq 0$$

where x_n denotes the set of all local variables of system n. Function $f_n(\cdot)$ is the local objective function of system n. g_n and h_n are compact forms of the inequality and equality constraints of system n. The DC-OPF formulation is shown as follows in which x_n, f_n, g_n, and h_n are discussed in details:

$$\min_{(x_n=\{p,\Theta\})} \sum_{u\in\Omega_G^n} f\left(p_u\right) \tag{12.2}$$

s.t.

$$h_n(x_n): \begin{cases} p_i - d_i = \sum_{j\in\Omega_i} \dfrac{\Theta_i - \Theta_j}{X_{ij}} & \forall i \in \{1, \ldots, N_B^n\} \quad (12.3) \\ \Theta_{ref} = 0 & (12.4) \end{cases}$$

$$g_n(x_n): \begin{cases} \underline{P_u} \leq p_i \leq \overline{P_u} & \forall u \in \Omega_G^n \quad (12.5) \\ \underline{PL_{ij}} \leq \dfrac{\Theta_i - \Theta_j}{X_{ij}} \leq \overline{PL_{ij}} & \forall ij \in \Omega_L^n \quad (12.6) \end{cases}$$

where the local decision variables, i.e., x_n, are the power output of DG units (p) and bus voltage angles (Θ). Parameter u is the index for generating units, and parameter d_i denotes the load at bus i. Ω_G^n is the set of units in system n. Ω_i denotes the set of all buses connected to bus i. Ω_L^n is the set of all branches in system n. N_B^n denotes the number of buses in system n. Function $f(p_u)$ is the generation cost function of DG unit u. Nodal power flow balance constraints are enforced by (12.3). Equality (12.4)

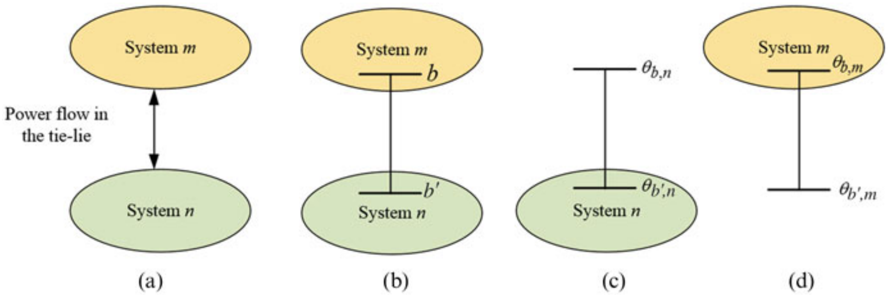

Fig. 12.6 Interconnected systems (**a**) Two interconnected systems, (**b**) the tie line links bus *b* of system *m* to bus b' of system *n*, (**c**) separating the two systems with considering system *n* controls the tie line flow, and (**d**) with considering system *m* controls the tie line flow

sets the voltage angle of the reference bus to zero. Inequalities (12.5) and (12.6) are, respectively, upper and lower bounds of DGs and line flow limits. A similar OPF can be formulated for system *m*.

All data used to formulate OPF*n* are exclusive local information of system *n*. No constraint, parameter, or variable of system *m* appears in OPF*n*. Similarly, OPF*m* is completely independent from system *n*. Thus, each system can solve its own local OPF regardless of another system. To schedule such a disconnected grid, a centralized optimization is solved for every system. Note that since we imagine that there exists no connection (coupling) between the systems, their OPF solutions are not interdependent.

Interconnected Systems

In a real distribution grid, DSO (system *m*) and MG (system *n*) are normally interconnected through a tie line(s), as shown in Fig. 12.6a. The power flow in this tie line affects the nodal power balance equations of both systems *m* and *n*. Hence, the tie line couples the OPF problems *n* and *m*. If the power is transferred from system *n* toward system *m*, the summation of power generated by local DG units of system *m* is less than the summation of its load. One can say that system *n* plays the role of a pseudo generating unit for system *m*, or in other words system *m* plays the role of a pseudo load for system *m*. Thus, in a fair electricity market, both systems *m* and *n* should be allowed to decide about the power flow in the common tie line. That is, the tie line flow couples the OPF problems *n* and *m*.

As shown in Fig. 12.6b, the power flow in the tie line depends on its voltage angles of ending terminals *b* and $b^{'}$. Thus, the voltage angles (in the case of AC-OPF, voltage magnitudes, and angels) of border buses of systems *m* and *n* couple the OPF problems *n* and *m*. To formulate OPF *n*, we consider that the tie line belongs to system *n* as depicted in Fig. 12.6c. OPF*n* is formulated as follows in which the local objective function of system *n* is to minimize the cost subject to constraints Eqs. (12.4)–(12.6) and (12.8)–(12.10):

$$\min_{\boldsymbol{x}_n=\{p,\Theta,\theta_{b,n},\theta_{b',n}\}} \sum_{u\in\Omega_G^n} f\left(p_u\right) \tag{12.7}$$

s.t.

$$p_i - d_i = \sum_{j\in\Omega_i} \frac{\theta_i - \theta_j}{X_{ij}} \qquad \forall i \in \left\{1, \ldots, N_B^n\right\}, i \neq b, i \neq b' \tag{12.8}$$

$$p_b - d_b = \frac{\theta_b - \theta_{b'}}{X_{bb'}} + \sum_{\substack{j \in \Omega_i \\ j \neq b'}} \frac{\theta_b - \theta_j}{X_{bj}} \tag{12.9}$$

$$p_{b'} - d_{b'} = \frac{\theta_{b'} - \theta_b}{X_{bb'}} \tag{12.10}$$

& (12.4), (12.5), (12.6)

$$\Theta \in \{\text{voltage angles of local buses of system } n\}$$

Note that Eqs. (12.8)–(12.10) are nodal power balance equations for all local buses of system n and border buses b and b'. A similar optimization can be formulated for system m. Since θ_b and $\theta_{b'}$ appear in both OPF problems n and m, we call them *shared variables*. The shared variables are a set of variables that belong to at least two autonomous systems. Each system m and n has the authority to decide about values of the shared variables θ_b and $\theta_{b'}$. However, if the systems determine the values of shared variables separately, different values might be obtained for a shared variable. For instance, if system n solves its OPF regardless of OPFm, θ_b might become 10 degree from the perspective of system n, whereas this shared variables might be 20 degree from the perspective of system m. This is not a feasible solution.

To obtain a feasible solution for the entire distribution grid, for every shared variable, a hard constraint needs to be formulated in the OPF problem of every system. Let $\theta_{b,\,n}$ denote the voltage angle of bus b from the perspective of system n, and $\theta_{b,\,m}$ denote the voltage angle of bus b from the perspective of system m. The following hard constraint needs to be enforced in the OPF problems m and n:

$$\theta_{b,m} = \theta_{b,n} \tag{12.11}$$

The hard constraint of the border bus b' is as

$$\theta_{b',m} = \theta_{b',n} \tag{12.12}$$

Thus, OPFn becomes

$$\min_{\boldsymbol{x}_n=\{p,\ \Theta,\theta_{b,n},\theta_{b',n}\}} \sum_{u\in\Omega_G^n} f\left(p_u\right) \tag{12.13}$$

s.t. (12.4), (12.5), (12.6), (12.8)–(12.12)

$$\Theta \in \{\text{voltage angles of local buses of system } n\}$$

While the optimization variables of OPFn are $\boldsymbol{x}_n = \left\{p, \Theta, \theta_{b,n}, \theta_{b',n}\right\}$, the optimization variables of OPFm are $\boldsymbol{x}_m = \left\{p, \Theta, \theta_{b,m}, \theta_{b',m}\right\}$. To solve OPF$n$, the values of $\theta_{b,\,m}$ and $\theta_{b',m}$ should be determined by system m and be sent to system n. Similarly, to solve OPFm, the values of $\theta_{b,\,n}$ and $\theta_{b',n}$ should be determined by system n and be sent to system m. Because of the hard constraints (12.11) and (12.12), the order of solving OPFn or OPFm affects the final solutions. For instance, assume that OPFm is solved (without the hard constraints), and we achieve $\theta_{b,\,m} = 10^{\circ}$ and $\theta_{b',m} = 20^{\circ}$. Then, constraints (12.11) and (12.12) force $\theta_{b,\,n}$ to 10° and $\theta_{b',n}$ to 20°. Now assume that OPFn is solved (without the hard constraints) and $\theta_{b,\,n} = 5^{\circ}$ and $\theta_{b',n} = 30^{\circ}$. Then, constraints (12.11) and (12.12) force $\theta_{b,\,m}$ to 5° and $\theta_{b',m}$ to 30°. Which solution is optimal? $\left\{\theta_b = 10^{\circ}, \theta_{b'} = 20^{\circ}\right\}$ or $\left\{\theta_b = 5^{\circ}, \theta_{b'} = 30^{\circ}\right\}$?

The hard constraints make the obtained solution suboptimal from the perspective of the whole power distribution grid. In the next section, we present an iterative algorithm to solve the OPF problems of the autonomous systems and ensure the optimality of results.

Distributed Operation of SoS-Based Active Distribution Grid

If DSO and MGs are islanded, they can solve their OPF subproblems independently. However, in the real world, these systems are interconnected through tie lines, and any decision made by a system affects decisions made by other MGs and DSO. To manage and control such an SoS, the shared variables and hard constraints (explained in the previous section) need to be coordinated. One approach is to assume an operator for the whole SoS. All MGs and DSO must share their data with the operator. This is against information privacy. MGs and DSO might not be willing to share their commercially sensitive information (e.g., information of generating units and loads) with other parties. Thus, a centralized framework might not be appropriate for the SoS operation.

An alternative is to deploy decentralized and distributed optimization algorithms to manage and control the SoS-based active distribution grid [42–49]. Applications of decentralized and distributed algorithms and cloud computing on complex engineering problems have seen increased interest recently [50]. Decentralized and distributed algorithms have been applied to a wide range of engineering problems, for instance, truck design, aircraft design, marketing, and engineering product design [51–53].

In this section, we discuss the application of decentralized optimization algorithms to solve the local OPF problems of DSO and MGs in a distributed manner. We focus on an approach, called analytical target cascading (ATC), and discuss how to coordinate the variables and hard constraints that link the optimization subproblems. We explain how to relax the effect of the hard constraints and to ensure that the obtained solution is not only feasible from the perspective of the autonomous systems and the whole SoS but also optimal.

A Brief Overview of Decentralized and Distributed Optimization Algorithms

Several decentralized and distributed optimization algorithms have been presented in the literature. Some of the most popular approaches, which have been widely used in power systems, are analytical target cascading (ATC), alternating direction method of multipliers (ADMM), auxiliary problem principle (APP), consensus+innovations (C + I), optimality condition decomposition (OCD), and proximal message passing (PMP). Although decentralized and distributed optimization algorithms have several similarities, these algorithms are better to be categorized into two groups, namely decentralized and distributed. Algorithms that need a central coordinator belong to the distributed category, whereas algorithms that do not need a central coordinator belong to the decentralized category. While many of the decentralized and distributed algorithms follow an iterative sequential solution procedure, a few algorithms follow a parallel solution procedure. Several sequential algorithms can be parallelized by introducing a coordinator. Thus, if one introduces a coordinator to parallelize a sequential decentralized algorithm, the algorithm becomes a parallel but distributed approach because of the introduction of a central coordinator.

While ADMM, ATC, APP, and PMP algorithms are based on augmented Lagrangian relaxation, OCD and C + I work based on the decomposition of first-order optimality conditions. The classical ADMM is a distributed algorithm; however, some efforts attempt to relax the need for a central coordinator and make the ADMM a decentralized algorithm [54]. ATC is a sequential decentralized algorithm; however, a coordinator can be used to convert ATC to a parallel distributed approach [55]. The APP is a parallel approach that has been applied to solve OPF in a decentralized manner. OCD, which does not need a coordinator, is an extension of the Lagrangian relaxation method [56, 57]. This method has been applied to solve OPF in multi-area power systems in a distributed fashion [9]. C + I is a decentralized method that aims at solving first-order optimality conditions in parallel [10]. Detailed discussions on distributed and decentralized algorithms are provided in [5–7].

Characteristics of Analytical Target Cascading

We deploy ATC to solve optimization problems of the systems in a decentralized manner. In the ATC procedure, an optimization problem is decomposed into several subproblems. The subproblems are put on different levels. Subproblems in upper levels are hierarchically connected to subproblems in lower levels. Subproblems at the same level are not connected. The ATC structure is similar to the problems defined in section "System of Systems Based Optimal Power Flow in Active Distribution Grids" as DSO and MGs are hierarchically connected while no connection exists between MGs at the same level. Systems in level l are known as parents of the systems in level $l + 1$, and systems in level $l + 1$ are children of systems in level l. Children located at the same level are not connected. In the context of active distribution systems, if the grid is considered as a graph model, systems are regarded as nodes, and tie lines are edges.

Shared variables between parents and children are defined as target and response variables. Response variables are indeed copies of target variables. A set of consistency constraints are formulated to enforce each pair of target-response to the same value. Based on the concept of Lagrangian and augmented Lagrangian relaxation, the consistency constraints are penalized in the objective functions of parents and children. Parents solve their optimization problems to determine the target values and propagate them down toward children. Children use the target values and determine their response variables. The response variables are sent up to the parents. Whenever the target and response values are close enough, ATC converges. ATC is proven to converge to the global optimum point if the optimization problems are convex [58].

Several options of penalty functions exist for penalization of the consistency constraint. Some of the most popular penalty functions are linear, quadratic, and exponential functions [5, 59]. This enhances the flexibility of ATC compared to several other methods such as APP. In addition, several coordination strategies exist. The one that is used in this chapter is augmented Lagrangian block coordinate descent [59, 60].

Mathematical Description of ATC

Assume that a following centralized optimization is formulated for the whole SoS:

$$\min_{x} F(x) \tag{12.14}$$

$$\text{s.t.}$$
$$g(x) \leq 0$$
$$h(x) = 0$$

where x is the set of decision variables of the whole SoS. Function F is the overall objective function, and g and h are inequality and equality constraints of the SoS.

Assume that the objective function and local constraints of autonomous systems of this SoS are separable. Also, assume that the autonomous systems are located at different levels of the hierarchy. The objective function and constraints of Eq. (12.14) are rewritten as follows:

$$\min_x \sum_{\forall l} \sum_{\forall a} f_{la}\left(x_{la}\right) \tag{12.15}$$

$$\text{s.t.}$$
$$g_{la}\left(x_{la}\right) \leq 0$$
$$h_{la}\left(x_{la}\right) = 0$$

$$x \in \left\{x_{11}, x_{22}, x_{23}, x_{24}, \ldots, x_{2(n+1)}, \ldots, x_{em}\right\}$$

$$\forall l \in \text{level}$$

$$\forall a \in \text{autonomous system}$$

where subscript la indicates autonomous system a in level l. x_{la} is the set of local variables of system a at level l. f_{la} is the objective function of system a at level l. g_{la} and h_{la} denote sets of local inequality and equality constraints of system a in level l.

Since the considered SoS in this chapter has two levels (see Fig. 12.6) and for the sake of simplicity and explanation, we consider a two-level structure, i.e., $l \in \{1, 2\}$. DSO is the upper level and MGs are located in the lower level. In the hierarchical ATC structure, systems in upper levels can be interconnected to the systems in the lower levels; however, the systems at the same level must not be connected. This is exactly the structure of the considered active distribution grid in this chapter. In the ATC structure, DSO is considered as the parent of MGs, and MGs are children of DSO.

The objective function and constraints of SoS are now decomposed as $\{F = f_{11} + f_{22} + f_{23} + \ldots + f_{2(n+1)}\}$, $\{g = g_{11} + g_{22} + g_{23} + \ldots + g_{2(n+1)}\}$ and $\{h = h_{11} + h_{22} + h_{23} + \ldots + h_{2(n+1)}\}$, where n is the number of systems in the second level (i.e., number of MGs). The optimization problem (12.15) is rewritten as

$$\min_x f_{11}\left(x_{11}\right) + \sum_{a=2}^{n+1} f_{2a}\left(x_{2a}\right) \tag{12.16}$$

$$\text{s.t.}$$
$$g_{11}(x_{11}) \leq 0, \quad g_{22}(x_{22}) \leq 0, \ldots, g_{2(n+1)}\left(x_{2(n+1)}\right) \leq 0$$
$$h_{11}(x_{11}) = 0, \quad h_{22}(x_{22}) = 0, \ldots, h_{2(n+1)}\left(x_{2(n+1)}\right) = 0$$

$$x \in \left\{x_{11}, x_{22}, x_{23}, x_{24}, \ldots, x_{2(n+1)}\right\}$$

We decompose the optimization problems. The optimization problem of system 11 (note that "11" refers to system 1 in level 1) is

$$\min_{x_{11}} f_{11}(x_{11}) \tag{12.17}$$

$$\text{s.t.}$$
$$g_{11}(x_{11}) \leq 0$$
$$h_{11}(x_{11}) = 0$$

And the optimization problem of system $2a$ is

$$\min_{x_{2a}} f_{2a}(x_{2a}) \tag{12.18}$$

$$\text{s.t.}$$
$$g_{2a}(x_{2a}) \leq 0$$
$$h_{2a}(x_{2a}) = 0$$

Since the autonomous systems are interconnected, x_{11} (x_{2a}) does not only include local variables of system 11 (12.2). We separate exclusive local variables of system 11 (and name them $\widetilde{x}_{11}$) and its shared variables with child a ($\forall a$) (and name them target variable t_{2a}). Now the optimization problem (12.17) is rewritten as

$$\min_{\left(\widetilde{x}_{11}, t_{2a}\right)} f_{11}\left(\widetilde{x}_{11}, t_{2a}\right) \tag{12.19}$$

$$\text{s.t.}$$
$$g_{11}(\tilde{x}_{11}, t_{2a}) \leq 0$$
$$h_{11}(\tilde{x}_{11}, t_{2a}) = 0$$

In the context of active distribution grids, target variables are voltage angles of border buses, i.e., ending terminals of tie lines that connect DSO and MGs as shown in Fig. 12.6. The optimization problem of system $2a$ is

$$\min_{\left(\widetilde{x}_{2a}, t_{2a}\right)} f_{2a}\left(\widetilde{x}_{2a}, t_{2a}\right) \tag{12.20}$$

$$\text{s.t.}$$
$$g_{2a}\left(\tilde{x}_{2a}, a\right) \le 0$$
$$h_{2a}\left(\tilde{x}_{2a}, t_{2a}\right) = 0$$

Problems (12.19) and (12.20) are not completely separable because of the target variable t_{2a}. To make these two optimizations separable, a set of response variables (r_{2a}) are introduced. A response variable is actually a copy of a specific target variable. The target variables are included in the parent's optimization, and the response variables are included in the children's optimizations. Problem (12.20) is rewritten as follows:

$$\min_{\left(\widetilde{x}_{2a}, r_{2a}\right)} f_{2a}\left(\widetilde{x}_{2a}, r_{2a}\right) \tag{12.21}$$

$$\text{s.t.}$$
$$g_{2a}\left(\tilde{x}_{2a}, r_{2a}\right) \le 0$$
$$h_{2a}\left(\tilde{x}_{2a}, r_{2a}\right) = 0$$

Now problems (12.19) and (12.21) are separable. However, solutions of (12.19) and (12.20) must be coordinated to find a feasible solution for the whole SoS as t_{2a} and r_{2a} are physically the same. Thus, a consistency constraint is formulated for each target-response pair and is enforced in the parent's and children's problems:

$$\text{C}: \quad t_{2a} - r_{2a} = 0 \tag{12.22}$$

The target variables are determined by the parent and are propagated down toward the children. The children determine the response copiers and propagate them up toward the parent. Let us explain the optimization problems and ATC in the context of active distribution grids. Consider Fig. 12.6 in which system m is a DSO and system n is an MG. The target variables of DSO are $\theta_{b,\,m}$ and $\theta_{b',m}$, and the response variables of MG are $\theta_{b,\,n}$ and $\theta_{b',n}$ (see Fig. 12.7), i.e.,

$$t \in \left\{\theta_{b,m}, \theta_{b',m}\right\}$$

$$r \in \left\{\theta_{b,n}, \theta_{b',n}\right\}$$

Local inequality and equality constraints g_{11} (and g_{2a}) and h_{11} (and h_{2a}) are indeed formulated by Eqs. (12.4)–(12.6) and (12.8)–(12.10). Local variables $\widetilde{x}_{11}$ (and $\widetilde{x}_{2a}$) are $\{p, \Theta\}$, i.e., $\widetilde{x}_{11} \in \{p_{11}, \theta_{11}\}$. The consistency constraint (12.22) is equivalent to hard constraints (12.11) and (12.12):

$$\text{C}: \theta_{2a} - \theta'_{2a} = 0 \tag{12.23}$$

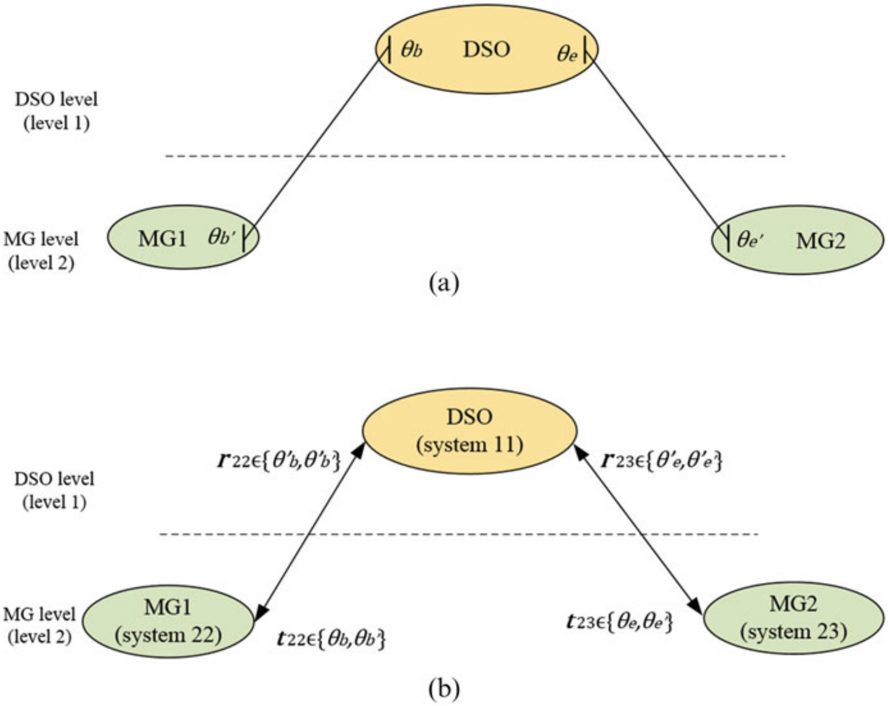

Fig. 12.7 Exchanges between DSO and MGs for (**a**) shared variables, and (**b**) target and response variables

where θ_{2a} (target) denotes the voltage angles determined by DSO and sent down to MGs, and θ'_{2j} (response) is the voltage angles determined by MGs and sent up to DSO. To handle the consistency constraints (i.e., hard constraints) and mitigate difficulties arisen by them, they are enforced in the local objective functions by a set of penalty functions $\pi(c)$. Thus, DSO's optimization problem (12.19) is rewritten as

$$\min_{(p_{11},\theta_{11},\theta_{2a})} f_{11}\left(p_{11},\theta_{11},\theta_{2a}\right)+\sum_{\forall a}\pi\left(\theta_{2a}-\theta'^{*}_{2a}\right) \tag{12.24}$$

$$\text{s.t.}$$
$$g_{11}\left(p_{11},\theta_{11},\theta_{2a}\right)\le 0$$
$$h_{11}\left(p_{11},\theta_{11},\theta_{2a}\right)=0$$

in which $\{p_{11},\theta_{11},\theta_{2a}\}$ are decision variables while θ'^{*}_{2a} (response) is a set of constants received from MGj. MGj's optimization problem (12.20) is rewritten as follows:

$$\min_{(p_{2a},\theta_{2a},\theta'_{2a})} f_{2a}\left(p_{2a},\theta_{2a},\theta'_{2a}\right)+\pi\left(\theta^{*}_{2a}-\theta'_{2a}\right) \tag{12.25}$$

$$\text{s.t.}$$
$$g_{2a}\left(p_{2a},\theta_{2a},\theta^{'}_{2a}\right)\leq 0$$
$$h_{2a}\left(p_{2a},\theta_{2a},\theta^{'}_{2a}\right)=0$$

in which $\{p_{2a},\theta_{2a},\theta'_{2a}\}$ are decision variables while θ^{*}_{2a} (target) is a set of constants received from DSO. The DSO and MGs iteratively solve (details of the solution procedure are explained in section "Mathematical Description of ATC") their OPF problems to update θ_{2a} and θ'_{2a} and enforce $\theta_{2a}-\theta'_{2a}$ to zero.

In the ATC method, several options exist to model penalty function $\pi(\cdot)$, e.g., linear, quadratic, and exponential function [56, 60]. One of the most popular penalty terms is an augmented Lagrangian that is a combination of a linear term and a quadratic function:

$$\lambda^{T}\left(\theta-\theta'\right)+\left\|\omega\circ\left(\theta-\theta'\right)\right\|^{2}_{2} \tag{12.26}$$

where λ and w are penalty multipliers, and "∘" denotes the Hadamard product. The objective functions of the optimization problems (12.24) and (12.25) are rewritten as follows:

$$\min_{(p_{11},\theta_{11},\theta_{2a})} f_{11}\left(p_{11},\theta_{11},\theta_{2a}\right)+\sum_{\forall a}\left\{\lambda^{T}_{2a}\left(\theta_{2a}-\theta'^{*}_{2a}\right)+\left\|\omega_{2a}\circ\left(\theta_{2a}-\theta'^{*}_{2a}\right)\right\|^{2}_{2}\right\} \tag{12.27}$$

$$\min_{(p_{2a},\theta_{2a},\theta'_{2a})} f_{2a}\left(p_{2a},\theta_{2\text{a}},\theta'_{2a}\right)+\left\{\lambda^{T}_{2a}\left(\theta^{*}_{2a}-\theta'_{2a}\right)+\left\|\omega_{2a}\circ\left(\theta^{*}_{2a}-\theta'_{2a}\right)\right\|^{2}_{2}\right\} \tag{12.28}$$

The quadratic term of the penalty function enhances the convergence speed of the iterative procedure. In addition, this term acts as a local convexifier, which is useful if local optimization problems are non-convex. However, the quadratic function adds a non-separable term in the objective function (i.e., $2\theta\times\theta^{'}$) that is a barrier in front of the parallel solution of local optimization problems of DSO and MGs.

Solution Procedure

The above procedure yields a set of local but coupled OPF problems, one for DSO and one for each MG. Indeed, the above procedure illustrates how to decompose the optimization problem (i.e., OPF in this chapter) of the whole SoS into local optimization problems of the autonomous systems. The next concern is "how to coordinate these local OPF problems since they are coupled through a set of shared variables." Thus, a coordination strategy is required to coordinate local optimization problems.

Several coordination strategies are presented in the literature for the ATC approach [59–61]. We present one of the most popular strategies called augmented Lagrangian block coordinate descent (AL-BCD). AL-BCD is an iterative sequential coordination strategy that consists of two loops, inner loop and outer loop. In the inner loop, the target and response values are updated while the penalty multipliers are kept constant. The main purpose of the inner loop is to enhance the accuracy of results. The inner loop stops when the difference between the values obtained for a shared variable in two consecutive iterations becomes less than a stopping threshold (see Step 4 of the algorithm). After inner-loop convergence, the convergence criterion of the outer loop is checked. The outer-loop convergence is achieved if the difference between each pair of target-response is less than a stopping threshold. If this constraint is satisfied, the algorithm stops; otherwise, the penalty multipliers are updated based on the obtained target and response values (see Step 5). Fig 12.8 shows the flowchart of the coordination strategy that is explained in detail as follows:

Step 1: Initialize local variables x of each subproblem, target values θ, response copiers $\theta^{'}$, penalty multipliers λ and ω, and parameter β, and set $k = 1$ and $q = 0$, where k and q denote, respectively, the outer and inner loop iteration indices.

Step 2: Set $q = q + 1$. DSO solves its local OPF subproblems using response values determined in the previous inner-loop iteration $q - 1$, i.e., $\theta^{'k,\, q\, -\, 1}$.

Step 3: Solve MGs' OPF subproblems using target values obtained in Step 2, i.e., $\theta^{k,\, q\, -\, 1}$.

Step 4: Check the following inner-loop convergence criterion:

$$\max\left(\left\|\theta^{k,q} - \theta^{k,q-1}\right\|, \left\|\theta'^{k,q} - \theta'^{k,q-1}\right\|\right) \leq \epsilon_{\text{inner}} \tag{12.29}$$

where ϵ_{inner} is the stopping threshold of the inner loop. If this criterion is satisfied and the rate of change of local objective functions is small enough, then stop the inner loop and go to Step 5; otherwise, go to Step 2.

Step 5: If $\max\{\|\theta^k - \theta^{'k}\|\} \leq \epsilon_{\text{outer}}$, where ϵ_{outer} is the outer-loop stopping threshold, the AL-BCD algorithm has converged; otherwise set $k = k + 1$ and $q = 0$ and update penalty multipliers as

$$\lambda^k = \lambda^{k-1} + \omega^{k-1} \circ \left(\theta^{k-1} - \theta'^{k-1}\right) \tag{12.30}$$

$$\omega^k = \beta \cdot \omega^{k-1} \tag{12.31}$$

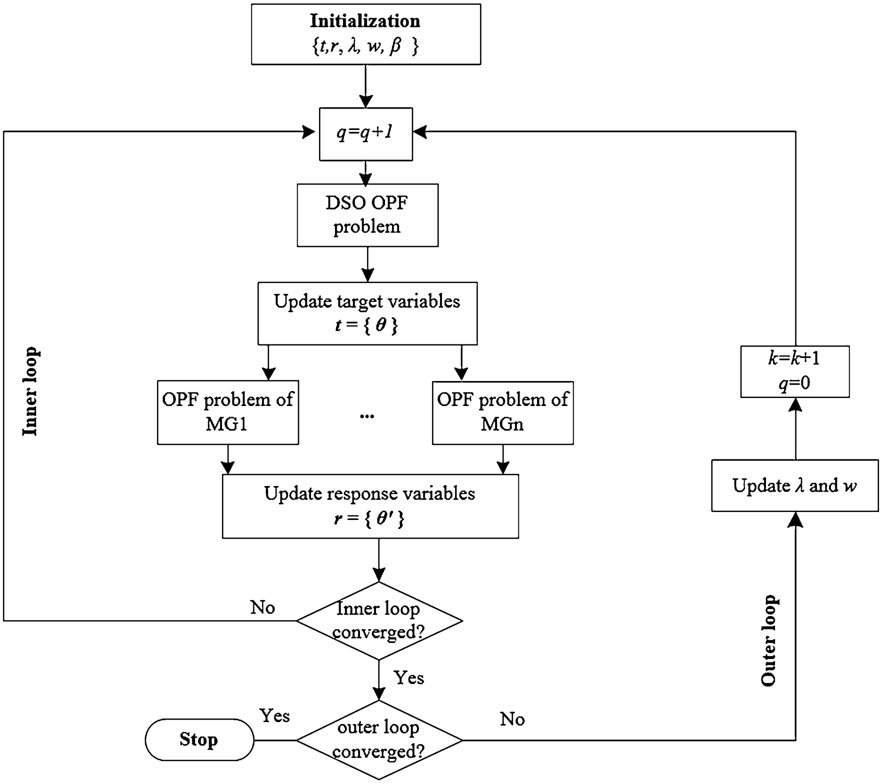

Fig. 12.8 Flowchart of the AL-BCD coordination strategy

and then go to Step 2. Parameter β should be larger than or equal to one, and it can reduce the computational cost. Although a wide range of β can be selected, based on the experience $\beta = 1$ can guarantee an acceptable accuracy.

One of the main questions for the above iterative solution procedure is "how to initialize variables and penalty multipliers." A bad initialization degrades the convergence performance of the algorithm and accuracy of its results. A good guess for the initial values potentially leads to a significant enhancement in the AL-BCD performance. This is a common issue for many decentralized and distributed optimization algorithms that need an initialization step. One of the most effective strategies is to use historical data of the system under study to find a good initial guess for variables, parameters, and penalty multipliers.

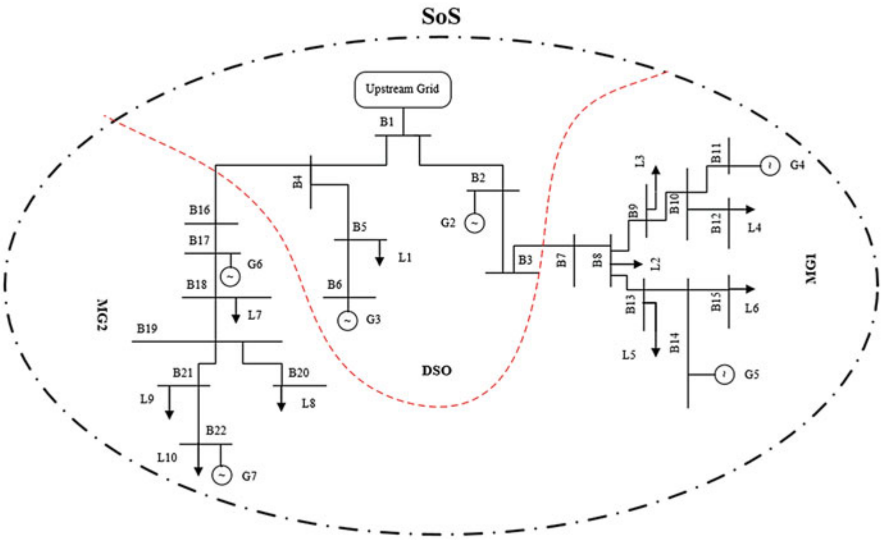

Fig. 12.9 A 22-bus SoS with three autonomous systems, one DSO, and two MGs

Table 12.1 Generating unit characteristics

Generation source	C (MBtu)	B (MBtu/MWh)	A (MBtu/MW2h)	P_{max} (MW)	P_{min} (MW)
Upstream grid	0	7	0	22	−22
G2	0	10	0	10	0
G3	0	8	0	2.5	0
G4	0	7	0	1.5	0
G5	0	3	0	1.8	0
G6	0	5	0	2.5	0
G7	0	25	0	1.9	0

Illustrative Example

A typical ADG is shown in Fig. 12.9. The SoS contains three systems, namely, DSO, MG1, and MG2. The whole SoS has 22 buses. The DSO includes six buses, one load, and three generating units. MG1 has nine buses, five loads, and three DGs. MG2 consists of seven buses, four loads, and two DGs. For the sake of simplicity, the admittance of all lines is considered to be 0.2 p.u. Characteristics of DGs and loads are shown in Tables 12.1 and 12.2. The voltage angles of buses 3, 4, 7, and 16 are shared variables. Indeed, θ_3 and θ_7 are shared variables between DSO and MG1, and θ_4 and θ_{16} are shared variables between DSO and MG2.

We analyze two cases:

Case 1: One operator is considered for the whole SoS, and the centralized OPF is implemented.

Table 12.2 Load data

Bus number	Load distribution (MW)
1	10.24
2	7.68
3	1.2288
4	0.9728
5	1.28
6	0.8704
7	3.3792
8	1.8432
9	2.8672
10	2.1504

Case 2: Each DSO and MG has its operator, and the decentralized OPF is implemented.

Case 1: Information privacy and autonomy of DSO and MGs are neglected. An operator is in charge of the whole SoS operation. The centralized OPF is formulated and solved. The operation costs of DSO, MG1, and MG2 are $196.12, $15.90, and $12.50, respectively (note that since the system is small and the scheduling horizon is only one interval, e.g., 5 min, the operation costs are not large).

Case 2: ADG is modeled as a two-level SoS in which DSO is in the upper level, and MGs are in the lower level. The DSO is the parent, and MGs are the children. An OPF is formulated for each DSO and MG. For instance, the detailed formulation of DSO OPF is as follows:

$$\min \left\{ \begin{array}{c} (7P_1 + 10P_2 + 8P_3) + \lambda_1 \left(\theta_3 - \theta_3'\right) + \left(\omega_1 \circ \left(\theta_3 - \theta_3'\right)\right)^2 + \\ \lambda_2 \left(\theta_7 - \theta_7'\right) + \left(\omega_2 \circ \left(\theta_7 - \theta_7'\right)\right)^2 + \lambda_3 \left(\theta_4 - \theta_4'\right) + \left(\omega_3 \circ \left(\theta_4 - \theta_4'\right)\right)^2 + \\ \lambda_4 \left(\theta_{16} - \theta_{16}'\right) + \left(\omega_4 \circ \left(\theta_{16} - \theta_{16}'\right)\right)^2 \end{array} \right\}$$

s.t.

$$\text{nodal power balance} \begin{cases} PL_{1,2} + PL_{1,4} - P_1 = 0 \\ PL_{2,3} + PL_{2,1} - P_2 = 0 \\ PL_{3,2} + PL_{3,7} = 0 \\ PL_{4,1} + PL_{4,16} + PL_{4,5} = 0 \\ PL_{5,4} + PL_{5,6} + 10.24 = 0 \\ PL_{6,5} + P_3 = 0 \end{cases}$$

Note: $PL_{i,j} = \frac{\theta_i - \theta_j}{0.2} \times 100$ and θ_3', θ_4',θ_7', and θ_{16}' are constants.

Note that for the sake of simplicity, line flow constraints are neglected. A tie line connects the border bus B3 of DSO to bus B7 of MG1, and another tie line links B4 of DSO to B16 of MG2. Hence, the voltage angles of buses B3, B4, B7, and B16 are shared variables among the autonomous systems. The DSO has four target variables (i.e., θ_3, θ_4, θ_7, and θ_{16}) and each MG has two response variables (i.e., θ_3 and θ_7 for MG1 and θ_4 and θ_{16} for MG2).

One drawback of such decentralized solution algorithms is the initialization of the penalty multipliers and shared variables. This drawback exists in many decentralized optimization algorithms that follow an iterative solution procedure. We initialize the targets and responses to zero. The decentralized algorithm is even more sensitive to initialization of the penalty multipliers. A bad initialization might degrade the solution accuracy and convergence process. Based on our experience, λ^0=200, w^0=200, and $\beta = 1$ are good initial values for the penalty multipliers. The inner and outer loops' convergence thresholds are $\epsilon_{\text{inner}} = 0.01$ and $\epsilon_{\text{outer}} = 1 \times 10^{-4}$. The AL-BCD algorithm converges after 72 outer-loop iterations with a total number of inner-loop iterations of 84. Figure 12.10 shows updating process of the target-response pairs over the course of iterations. When the difference of each target and response in two consecutive iterations is less than 0.01 (i.e., $|t^k - t^{k-1}| \leq 0.01$ and $|r^k - r^{k-1}| \leq 0.01$) the inner loop stops. Then, the stopping criterion of the outer loop, i.e., $|t^k - r^k| \leq 0.0001$, is checked. If this criterion is satisfied, the convergence is achieved; otherwise, the penalty multipliers are updated as the inner loop restarts. A smaller stopping criterion improves the accuracy of the results; however, this increases the number of iterations. Note that in several iterations the difference between some of the target-response pairs is less than the stopping threshold; however, the algorithm stops when the differences between all target-response pairs become less than the stopping threshold.

The average difference between the target-response values over the course of iterations is depicted in Fig. 12.11. The AL-BCD algorithm stops when the differences between all pairs of target-response become less than the stopping threshold $\epsilon_{\text{outer}} = 1 \times 10^{-4}$. Hence, the average error between the target-response pairs must be less than the stopping criterion upon the convergence.

The operation costs of DSO, MG1, and MG2 are \$196.73, \$15.90, and \$12.50, respectively. The total SoS operation cost obtained by the decentralized algorithm is \$225.13. In order to evaluate the performance of the AL-BCD algorithm, two indices are considered. The first index measures the relative distance between the total costs of the decentralized optimization compared to the optimal value calculated by the centralized OPF (note that the centralized OPF provides benchmark results):

$$\text{rel} = \frac{|f_{\text{cent}} - f_{\text{dec}}|}{f_{\text{cent}}} \tag{12.32}$$

The second index measures how much power mismatch exists between the tie lines. In other words, the total power mismatch is the summation of all mismatches of power exchange between DSO and MG1, and DSO and MG2:

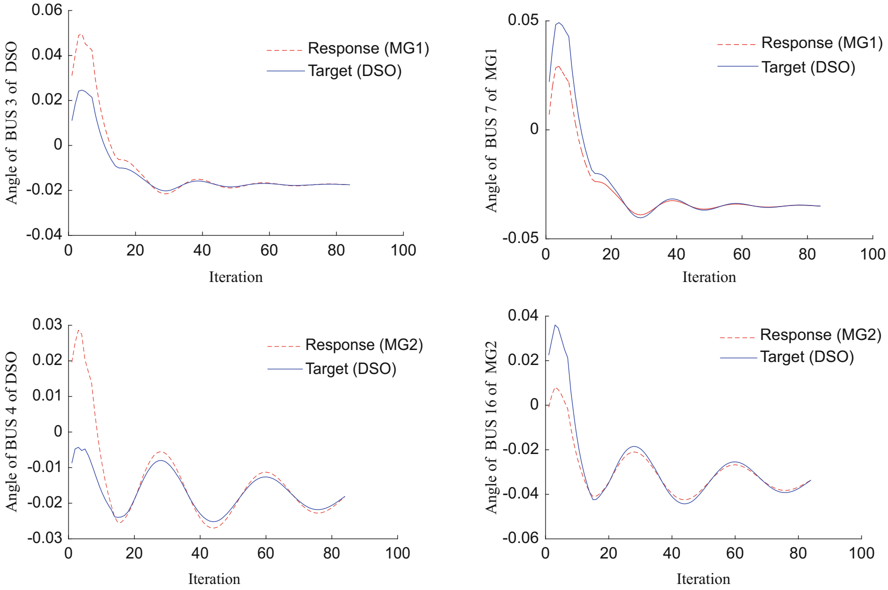

Fig. 12.10 The updating process of target and response values

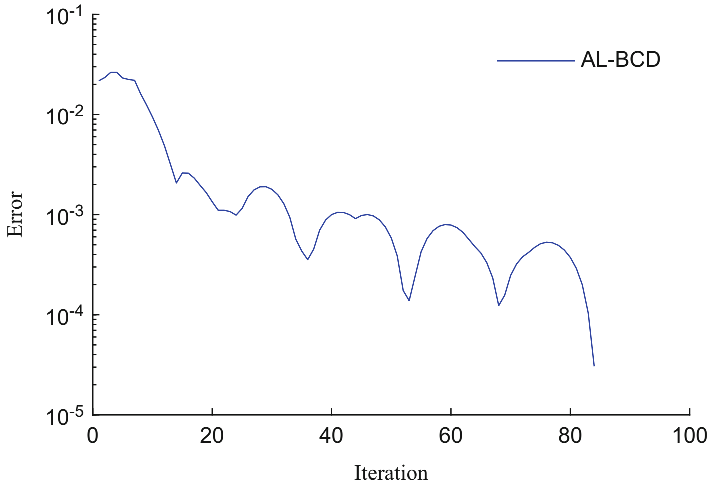

Fig. 12.11 The average of differences between targets and responses

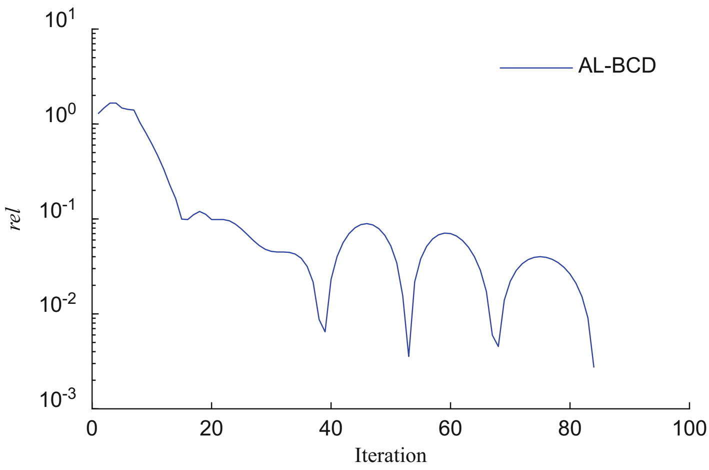

Fig. 12.12 The convergence measure rel over the course of iterations

$$P_{\text{mis}} = \left| \frac{P_l^{\text{cent}} - P_l^{\text{dec}}}{P_l^{\text{cent}}} \right| \tag{12.33}$$

Figures 12.12 and 12.13 show rel and P_{mis} indices over the course of optimization. These two convergence measures gradually decrease. Note that at the optimal point, rel and P_{mis} are zero. The updating procedure of λ (penalty multipliers) over the course of iterations is shown in Fig. 12.14. Selecting good initial guesses for multipliers, i.e., good guesses that are close to the optimal values of λ, potentially reduces the number of iterations.

Concluding Remarks

The SoS-based management framework is potentially promising for collaboration between the autonomous entities in power systems. In this chapter, an SoS framework was presented for operation of active distribution grids that include multiple microgrids. This framework allowed DSO and MGs to operate based on their objectives and rules while taking into consideration the information privacy of the autonomous systems. To model physical interactions among DSO and MGs, a set of hard constraints was formulated. Although the hard constraints ensure the feasibility of the whole active distribution grid, they move the final solution toward a suboptimal point if they are directly included in the local optimizations of DSO and MGs. The hard constraints were relaxed on the local objective functions by augmented Lagrangian functions. The augmented Lagrangian block coordination descent, which is a coordination strategy for distributed optimization, was presented

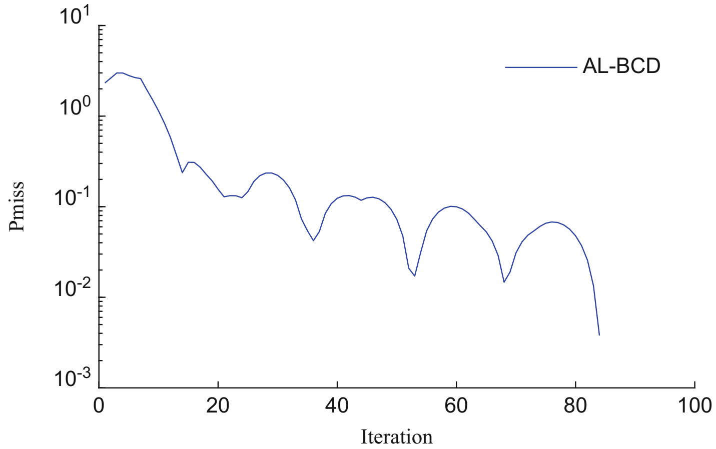

Fig. 12.13 The convergence measure P_{mis} (i.e., mismatch in tie-line flows) over the course of iterations

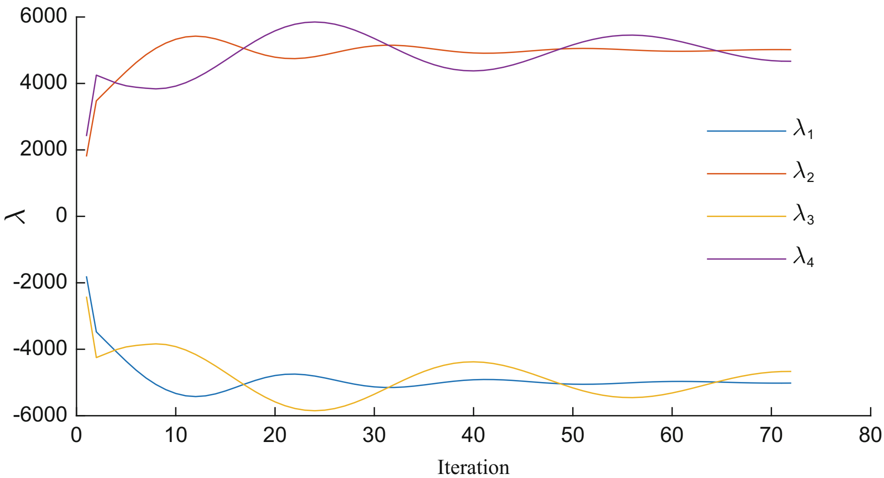

Fig. 12.14 Values of penalty multipliers over the course of iterations

to handle the shared variables among DSO and MGs. Although such an iterative approach provided good results, its convergence is dependent on the choice of initial conditions that is one of the main drawbacks of such algorithms. One promising direction of research is to reduce the sensitivity of the augmented Lagrangian block coordination descent to the choice of initial values. Another possible future research direction is to consider uncertainties of renewable energy recourses and load.

References

1. Idema, R., & Lahaye, D. J. (2014). *Computational methods in power system analysis*. New York: Springer.
2. Wood, A. J., & Wollenberg, B. F. (2012). *Power generation, operation, and control*. New York: John Wiley & Sons.
3. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., Pardalos, P. M., Blaabjerg, F., & Madni, A. M. (2018). *Sustainable interdependent networks: From theory to application*. Cham: Springer.
4. Amini, M. H., Boroojeni, K. G., Iyengar, S., Blaabjerg, F., Pardalos, P. M., & Madni, A. M. (2018). A panorama of future interdependent networks: From intelligent infrastructures to smart cities. In *Sustainable interdependent networks* (pp. 1–10). Cham: Springer.
5. Kargarian, A., Mohammadi, J., Guo, J., Chakrabarti, S., Barati, M., Hug, G., et al. (2016). Toward distributed/decentralized DC optimal power flow implementation in future electric power systems. *IEEE Transactions on Smart Grid, 3*, 1249–1258.
6. Molzahn, D. K., Dörfler, F., Sandberg, H., Low, S. H., Chakrabarti, S., Baldick, R., et al. (2017). A survey of distributed optimization and control algorithms for electric power systems. *IEEE Transactions on Smart Grid, 8*, 2941.
7. Wang, Y., Wang, S., & Wu, L. (2017). Distributed optimization approaches for emerging power systems operation: A review. *Electric Power Systems Research, 144*, 127–135.
8. Marvasti, A. K., Fu, Y., DorMohammadi, S., & Rais-Rohani, M. (2014). Optimal operation of active distribution grids: A system of systems framework. *IEEE Transactions on Smart Grid, 5*, 1228–1237.
9. Conejo, A. J., Nogales, F. J., & Prieto, F. J. (2002). A decomposition procedure based on approximate Newton directions. *Mathematical Programming, 93*, 495–515.
10. Kar, S., Hug, G., Mohammadi, J., & Moura, J. M. (2014). Distributed state estimation and energy management in smart grids: A consensus + innovations approach. *IEEE Journal of Selected Topics in Signal Processing, 8*, 1022–1038.
11. Kotov, V. (1997). *Systems of systems as communicating structures*. Hewlett Packard Laboratories.
12. Lukasik, S. J. (1998). Systems, systems of systems, and the education of engineers. *AI EDAM, 12*, 55–60.
13. Pei, R. S. (2000). System of Systems Integration (SoSI)-A “SMART” Way of Acquiring Army C412WS Systems. In *Summer Computer Simulation Conference* (pp. 574–579).
14. Carlock, P. G., & Fenton, R. E. (2001). System of Systems (SoS) enterprise systems engineering for information-intensive organizations. *Systems Engineering, 4*, 242–261.
15. Sage, A. P., & Cuppan, C. D. (2001). On the systems engineering and management of systems of systems and federations of systems. *Information Knowledge Systems Management, 2*, 325–345.
16. Jamshidi, M. (2011). *System of systems engineering: innovations for the twenty-first century* (Vol. 58). New York: John Wiley & Sons.
17. Marvasti, A. K. (2014). *System of systems based decision-making for power systems operation*. Mississippi: Mississippi State University.
18. Kargarian, A., Falahati, B., & Fu, Y. (2013). Optimal operation of distribution grids: A system of systems framework. In *Innovative Smart Grid Technologies (ISGT), 2013 IEEE PES* (pp. 1–6).
19. Kargarian, A., Fu, Y., Liu, P., & Wang, C. (2014). A system of systems engineering approach for unit commitment in multi-area power markets. In *PES General Meeting| Conference & Exposition, 2014 IEEE* (pp. 1–5).
20. Kargarian, A., & Fu, Y. (2014). System of systems based security-constrained unit commitment incorporating active distribution grids. *IEEE Transactions on Power Systems, 29*, 2489–2498.
21. Mehrtash, M., Raoofat, M., Mohammadi, M., & Zareipour, H. (2016). Fast stochastic security-constrained unit commitment using point estimation method. *International Transactions on Electrical Energy Systems, 26*, 671–688.

22. Kargarian, A., Fu, Y., & Wu, H. (2016). Chance-constrained system of systems based operation of power systems. *IEEE Transactions on Power Systems, 31*, 3404–3413.
23. Sage, A. P. (2003). Conflict and risk management in complex system of systems issues. In *Systems, man and cybernetics. IEEE International Conference on, 2003* (pp. 3296–3301).
24. Parks, R. C., Jung, R. A., & Ramotowski, K. O. (2004) Attacking agent-based systems. In *Multi-Agent Security and Survivability, 2004 IEEE First Symposium on, 2004* (pp. 31–34).
25. Monarch, I., & Wessel, J. (2005). Autonomy and interoperability in system of systems requirements development. In *16th IEEE International Symposium on Software Reliability Engineering, Chicago, IL*
26. Chowdhury, S., & Crossley, P. (2009). *Microgrids and active distribution networks*. London: The Institution of Engineering and Technology.
27. Lasseter, R. H. (2002). Microgrids. In *Power Engineering Society Winter Meeting, 2002. IEEE* (pp. 305–308).
28. Bollen, M. H., & Hassan, F. (2011). *Integration of distributed generation in the power system* (Vol. 80). New York: John Wiley & Sons.
29. Bayod-Rújula, A. A. (2009). Future development of the electricity systems with distributed generation. *Energy, 34*, 377–383.
30. Lopes, J. P., Hatziargyriou, N., Mutale, J., Djapic, P., & Jenkins, N. (2007). Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities. *Electric Power Systems Research, 77*, 1189–1203.
31. Pepermans, G., Driesen, J., Haeseldonckx, D., Belmans, R., & D'haeseleer, W. (2005). Distributed generation: Definition, benefits and issues. *Energy Policy, 33*, 787–798.
32. Khodaei, A., & Shahidehpour, M. (2013). Microgrid-based co-optimization of generation and transmission planning in power systems. *IEEE Transactions on Power Systems, 28*, 1582–1590.
33. Algarni, A. A., & Bhattacharya, K. (2009). Disco operation considering DG units and their goodness factors. *IEEE Transactions on Power Systems, 24*, 1831–1840.
34. Soroudi, A., Ehsan, M., Caire, R., & Hadjsaid, N. (2011). Possibilistic evaluation of distributed generations impacts on distribution networks. *IEEE Transactions on Power Systems, 26*, 2293–2301.
35. Borghetti, A., Bosetti, M., Grillo, S., Massucco, S., Nucci, C. A., Paolone, M., et al. (2010). Short-term scheduling and control of active distribution systems with high penetration of renewable resources. *IEEE Systems Journal, 4*, 313–322.
36. Ahn, S.-J., Nam, S.-R., Choi, J.-H., & Moon, S.-I. (2013). Power scheduling of distributed generators for economic and stable operation of a microgrid. *IEEE Transactions on Smart Grid, 4*, 398–405.
37. Logenthiran, T., Srinivasan, D., Khambadkone, A. M., & Aung, H. N. (2012). Multiagent system for real-time operation of a microgrid in real-time digital simulator. *IEEE Transactions on Smart Grid, 3*, 925–933.
38. Safdarian, F., Ardehali, M., & Gharehpetian, G. (2014). Ramp rate effect on maximizing profit of a microgrid using gravitational search algorithm. In *Proceedings of The 2014 IAJC-ISAM International Conference*.
39. Bagherian, A., & Tafreshi, S. M. (2009). A developed energy management system for a microgrid in the competitive electricity market. In *PowerTech, 2009 IEEE Bucharest* (pp. 1–6).
40. Mohammadi, M., Hosseinian, S., & Gharehpetian, G. (2012). GA-based optimal sizing of microgrid and DG units under pool and hybrid electricity markets. *International Journal of Electrical Power & Energy Systems, 35*, 83–92.
41. Braun, M., & Strauss, P. (2008). A review on aggregation approaches of controllable distributed energy units in electrical power systems. *International Journal of Distributed Energy Resources, 4*, 297–319.
42. Amini, M. H., Jaddivada, R., Mishra, S., & Karabasoglu, O. (2015). Distributed security constrained economic dispatch. In *Innovative Smart Grid Technologies-Asia (ISGT ASIA), 2015 IEEE* (pp. 1–6).

43. Mohammadi, J., Kar, S., & Hug, G. (2017). Fully distributed corrective security constrained optimal power flow. In *PowerTech, 2017 IEEE Manchester* (pp. 1–6).
44. Amini, M. H., Nabi, B., & Haghifam, M. -R. (2013). Load management using multi-agent systems in smart distribution network. In *Power and Energy Society General Meeting (PES), 2013 IEEE* (pp. 1–5).
45. Mohammadi, J., Hug, G., & Kar, S. (2018). Agent-based distributed security constrained optimal power flow. *IEEE Transactions on Smart Grid, 9*(2), 1118–1130.
46. Mohammadi, A., Mehrtash, M., & Kargarian, A. (2018). Diagonal quadratic approximation for decentralized collaborative TSO + DSO optimal power flow. *IEEE Transactions on Smart Grid,* 1. https://doi.org/10.1109/TSG.2018.2796034, 1.
47. Kargarian, A., Mehrtash, M., & Falahati, B. (2017). Decentralized implementation of unit commitment with analytical target cascading: A parallel approach. *IEEE Transactions on Power Systems, 1*, 1.
48. Safdarian, F., Ciftci, O., & Kargarian, A. (2018). A time decomposition and coordination strategy for power system multi-interval operation. *Presented at the IEEE Power and Energy Society General Meeting, Portland, OR*.
49. Mohammadi, A., Mehrtash, M., Kargarian, A., & Barati, M., Tie-line characteristics based partitioning for distributed optimization of power systems. *IEEE Power and Energy Society General Meeting, Portland, OR*.
50. Amini, M. H., Boroojeni, K. G., Dragičević, T., Nejadpak, A., Iyengar, S., & Blaabjerg, F. (2017). A comprehensive cloud-based real-time simulation framework for oblivious power routing in clusters of DC microgrids. In *DC Microgrids (ICDCM), 2017 IEEE Second International Conference on, 2017* (pp. 270–273).
51. Kim, H. M., Kokkolaras, M., Louca, L. S., Delagrammatikas, G. J., Michelena, N. F., Filipi, Z. S., et al. (2002). Target cascading in vehicle redesign: A class VI truck study. *International Journal of Vehicle Design, 29*, 199–225.
52. Allison, J., Walsh, D., Kokkolaras, M., Papalambros, P., & Cartmell, M. (2006). Analytical target cascading in aircraft design. *44th AIAA aerospace sciences meeting and exhibit* (pp. 9–12).
53. Michalek, J. J., Feinberg, F. M., & Papalambros, P. Y. (2005). Linking marketing and engineering product design decisions via analytical target cascading. *Journal of Product Innovation Management, 22*, 42–62.
54. Chen, C., He, B., Ye, Y., & Yuan, X. (2016). The direct extension of ADMM for multi-block convex minimization problems is not necessarily convergent. *Mathematical Programming, 155*, 57–79.
55. Kargarian, A., Fu, Y., & Li, Z. (2015). Distributed security-constrained unit commitment for large-scale power systems. *IEEE Transactions on Power Systems, 30*, 1925–1936.
56. Cohen, G. (1980). Auxiliary problem principle and decomposition of optimization problems. *Journal of Optimization Theory and Applications, 32*, 277–305.
57. Hug-Glanzmann, G., & Andersson, G. (2009). Decentralized optimal power flow control for overlapping areas in power systems. *IEEE Transactions on Power Systems, 24*, 327–336.
58. Michelena, N., Park, H., & Papalambros, P. Y. (2003). Convergence properties of analytical target cascading. *AIAA Journal, 41*, 897–905.
59. DorMohammadi, S., & Rais-Rohani, M. (2013). Exponential penalty function formulation for multilevel optimization using the analytical target cascading framework. *Structural and Multidisciplinary Optimization, 47*, 599–612.
60. Tosserams, S., Etman, L., Papalambros, P., & Rooda, J. (2006). An augmented Lagrangian relaxation for analytical target cascading using the alternating direction method of multipliers. *Structural and Multidisciplinary Optimization, 31*, 176–189.
61. Li, Y., Lu, Z., & Michalek, J. J. (2008). Diagonal quadratic approximation for parallelization of analytical target cascading. *Journal of Mechanical Design, 130*, 051402.

Chapter 13
Adoption, Implementation, and Performance of Green Supply Chain Management: The Case of Coal Power Generation Industry in Indonesia

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Introduction

The awareness of sustainability among SCs has been increasing since the World Commission on Environment and Development (WCED) presented its report at a press conference in London, England on 27 April 1987 entitled as "Our Common Future" [4]. "Our Common Future" is identified as a starting strategy for landing sustainable future and warned the world about the importance of natural properties for making progress toward economic development. Later on, in 2007, the Irish National Climate Change Strategy [8] outlined the global challenge as the global warming fetch up by human-made greenhouse gas emissions. The economic consensus can prove that the costs of inaction against the global warming will significantly be higher than costs of actions in the long term. Therefore, innovative and progressive climate change policies consorted with low-carbon technology are required to design and enforce for consistency of global economic growth with sustainability.

Sustainability is required the long-term policy. Several targets need to be defined to tackle long-term sustainability-related issues. For instance, adopt new

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policies, construct/reconstruct/equip the infrastructures, develop innovative clean technologies, redesign SCs, and redefine business models. Therefore, organizations are required to enhance their strategy to sustain their business and profitability while remaining competitive in the marketplace. Although, many companies identify the sustainability in the SC as one of the most critical and challenging activities, such that the United Nation states the sustainability in practice through the SC management (SCM) (https://www.unglobalcompact.org/what-is-gc/our-work/supply-chain).

SCM has required a multi-criteria decision-making (MCDM) system, which allows structuring a complex decision process for obtaining a solution based on (semi) quantitative criteria and the power of each criterion on SCM. More specifically where environmental, economic, and social goals are assessed at the same time, specific decisions are demanded to emphasize the influence of each criterion. Therefore, studying the inner dependencies and outer dependencies among and between the criteria is relevant for decision-makers to capture and represent the concepts of influencing or being influenced.

One of the inevitable phenomena for sustainability is activities and businesses related to energy systems. Among all energy providing resources, fossil fuel has the highest adverse effect on the development of green supply chain (GSC). In addition in most developing countries, the fossil fuel has the highest percentage of utilization.

Therefore, regarding the geographical factors and growth in economical aspect, we developed a sustainability index for the supply change management of coal industry in Indonesia as one of the largest coals producer in the world which located in the center of economic growth in Asia. To address the effect of each factor on interdependency of SC network in Coal Industry of Indonesia, the analytical hierarchy process (AHP) has been used in this study.

Background of GSCM

According to the [25] green SCM (GSCM) has included the internal GSCM, external GSCM and "corporate social responsibility" (CSR).

The internal GSCM is associated with environmental performance, environmental collaboration with customers, and staff involvement, that can improve the operational performances [27]. The "internal GSCM" is required the "internal green management" and "sustainable product design" as the foundation for implementation, when directly will effect on economic performance [26]. Internal GSCM practice on ISO14001 certification.

The external GSCM is associated with partners or stakeholders such as suppliers and customers and required the strong "diversity management," accurate "safety management" plus "community development and involvement." Governmental demand is a crucial driver moving the external GSCM implementation [23]. External GSCM is also seeking the international trade communities for environmentally friendly operations. “Green purchasing,” “customer cooperation,” and “investment recovery” are three customer related factors for practicing the external GSCM [28]. In addition, Fang & Zhang [10] are considered the “eco-design” for “external GSCM” to exert significant influence on firm performance.

Along with the internal GSCM and external GSCM, the CSR brings the moral management in the business horizon of a firm [5]. The Carroll’s pyramid of CSR [5] has underlined the economic profitability as the result of obeying the law, where the ethical behavior is the requirement for legal intendance, and that is the outcome of a good cooperative relationship.

This research bounded all factors of “internal GSCM,” “external GSCM,” and “CSR” into the principle of “Adoption” [14], “Implementation” [3, 6, 6, 9], and “Performance” [21] (A.I.P) of GSCM to explore the fundamental factors or criteria of GSCM for adjusting the sustainability benchmark. Following this section, we investigate each factor and its relevant contents.

Market Forces

- Consumers, retailers, and financial stakeholders may demand products considered green from the suppliers and require that the company follow sustainable practices.
- In the close future access to capital markets may be restricted only to businesses that are deemed to be ethical or environment-friendly.
- Companies expected suppliers to perform GSCM practices based on environmental (e.g., ISO 14001) and social (SA 8000) standards.
- a competition in the marketplace may require a company to offer products considered as socially responsible, green, or sustainable.

Policy and Regulations

- Governmental policy and regulations factors are requiring that companies adhere to certain environmental standards.
- Environmental regulation for manufacturers concerns a standard target of pollutants generated by products and manufacturing process to eliminate environmental hazards.
- The industry standards such as ISO 14001, ISO 14040, EuP, RoHS, and WEEE require suppliers to carry audits and certifications.

Internal Factors

- Push business to engage in green sourcing practices or forcing suppliers to adopt or adapt processes to be more environment-friendly and initiative.
- The leading private sector or top management vision can demonstrate significant movement toward greening procurement practices.
- Treatment of labor force, protecting and preserving the fundamental rights of employees, including their health and safety and human rights can bring employees commitment.

Marketing and Public Relations

- Putting more efforts of companies to create a value proposition for the customers, especially when the "environment-friendly" product is more expensive to increase the sale as the nature of the business.
- Create awareness of the practices through the use of logos and co-branding, to convince customers to buy green products.
- Non-Governmental Organizations (NGOs) can run boycotts or adverse publicity campaigns designed to shame the company into offering more sustainable products.

Waste Reduction

- Includes reuse, remanufacturing, and recycling of materials into new materials or other products.
- Change the supplied product and trying to manage the by-products of supplied inputs.
- Managing the short-term financial results, and risk factors such as harm resulting from products, environmental waste, and worker and public safety.

International Certificates

- Firms that implement sustainability in their corporate culture also request suppliers to develop and maintain an environmental management system (EMS) even though a buyer does not require its supplier to certify the system.
- Firms require suppliers to have an EMS that is certified as fully compliant with one of the recognized international standards, such as ISO 14001 or European Union Eco-Management and Audit Scheme (EMAS).
- Supplier's information about their environmental aspects, certification, activities, and management systems are also necessary for GSCM.

Eco-Design

- Includes green procurement practices (purchasing environment-friendly materials/products), total quality environmental management (internal performance measurement), and transportation.
- Environmental technologies are broadly defined to include design, equipment, and operating procedures that limit or reduce negative impacts of products or services on the natural environment.
- Greening of the existing product (e.g., using more recycled content, using biodegradable materials or alternative sources of fuels) and developing new green sustainable products (e.g., reverse logistics, design for disassembly, and using renewable resources).

Pollution Prevention

- Eliminate or minimize waste (energy, emissions, chemical/hazardous, solid wastes)

- Reducing carbon footprint, product lifecycle cost management and reducing transportation costs.
- Adopted green procurement practices for specific products such as recycled-content office paper, renewable energy, paints, cleaners, etc.

Operational Aspects

- GSCM could give the benefit of cost savings due to the use of reusable materials while at the same time reducing and minimizing ecological footprint.
- Flexibility is defined as having the capability to provide products or services that meet the individual demands of customers.
- By flexibility, companies can achieve rapid response to meet individual customer requirements. SC directly impacts on customer's delivery. Then customer satisfaction by measuring and improving delivery can increase the competitiveness of companies.

Economic Aspects

- Long-term profits are required by the high quality of logistics services and customer satisfaction.
- Quick responsiveness of companies to introduce a new product as well as product deliveries could help to evaluate the level of competitiveness.
- Efficiency is expressed by measurements such as the return on investment, inventory, total logistic cost, truck fill rate, delivery cost, process time, resource utilization, production management, etc.

Environmental Aspects

- Environmental performance is focusing on the company's activities in lowering negative impact on the natural environment.
- How company influences the environment which includes CO2 emission, energy use from natural resources (e.g., fuel, water, and land use), and waste and recycling.
- Environmental performance can enhance the financial performance by minimizing both hazardous and non-hazardous waste, which leads to better utilization of natural resources, reduces operating costs, and improves efficiency.

Social Aspects

- Health and safety involve the number and type of work-related accidents (e.g., fatal and major injuries).
- Employment can be considered as overall job creation or reduction, and the organizational culture inside the company reflects working conditions and employees morale.
- Noise emission is included in social aspects which is the most disturbing factor in residential areas and makes the timing of operational industry more important (day or night shift).

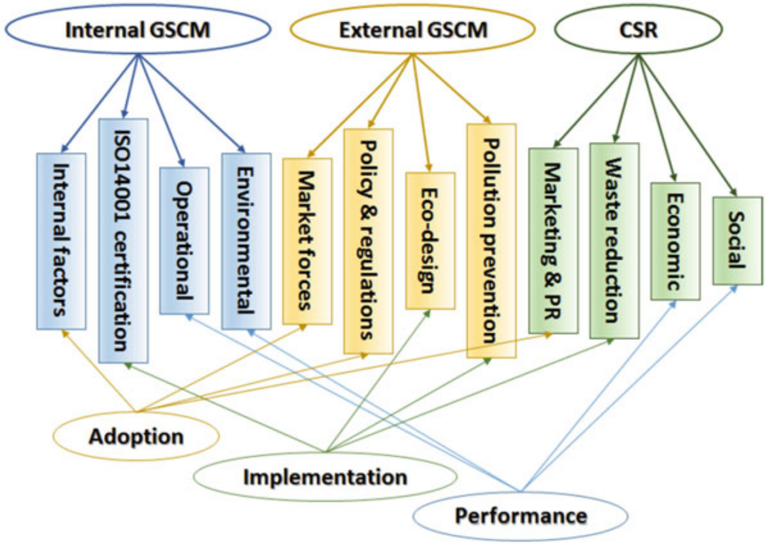

Fig. 13.1 Classification scheme of A.I.P for "internal GSCM," "external GSCM" and CSR

Figure 13.1 designs the classification scheme of A.I.P and its involvement of "internal GSCM," "external GSCM," and CSR.

Sustainability Analysis in SC Network

According to Seuring [22], there are four modeling techniques that could be used to assess GSCM such as life-cycle assessment (LCA) models [12], equilibrium models [19], MCDM [20], and analytical hierarchy process (AHP) [13]. LCA models assessed environmental impacts on the wide network of SC. The purpose of LCA is to minimize the effect of environmental impacts on SC. Equilibrium models balanced environmental and economic factors and finding an equilibrium or optimal solution. This model evaluates the overall equilibrium among given set of networks but does not directly aim at their decisions. MCDM model is usually not so much focus on the optimization of economic and environmental criteria or reaching an equilibrium situation but rather dealing to balance trade-off among multi objective problems. AHP is also an MCDM technique, but it allows structuring a decision process thereby obtaining a solution based on semi-quantitative criteria and respective weights. AHP allows evaluating not only complex decision situations, where environmental and economic goals are assessed at the same time but also more specific decisions, such as looking at the role of hazardous substance management and supplier development practices. In comparison with MCDM and equilibrium model, the aims of AHP are not so much reaching an equilibrium but rather focusing on toward the complexity of decision making and emphasizing the influence of the decision makers. Based on Seuring [22] modeling approaches for GSCM, equilibrium and MCDM model build trade-offs situation among environmental and economic goals. According to the Seuring [22] approaches, AHP allows choosing criteria that represent either win-win situations or minimum standards. AHP model allows evaluating performance issues of each company as well as SC in total. Therefore, the generalization of AHP model which is called analytic network process (ANP) [15] is used for the decision-making process in this study.

Analytic Network Process

The components of a decision network are clusters, the clusters' elements, and links between elements. In each cluster there are a parent and children elements, links between the parent and children make up the pairwise comparison set for AHP [1]. These links will express the dependencies, interactions, influences, and feedback in the system. Links between elements within the same cluster are called inner dependencies, and between parent elements are called outer dependencies. The inner and outer dependencies are relevant for decision-makers to capture and represent the concepts of influencing or being influenced, between clusters and between elements concerning a specific element.

The traditional ANP method deals with normalization to obtain weighted super-matrix. It is done by cutting each criterion in a column by some clusters so that each column reaches exact unity. In other words, each group has equal weight. Even though this method of normalizing the super-matrix is simple, however, it is irrational to assume equal weights because the effect of one cluster on the other groups may be different in degree [7].

Decision Making Trial and Evaluation Laboratory (DEMATEL) [16] method has been widely used for building and analyzing a structural models involving causal relationships between complex factors [17]. It is used to confirm the relationship between different dimension and criteria to develop our understanding of the complex issues by building a network relationship map. By using this map, the direction and intensity of the direct and indirect relationships that flow between components could be analyzed.

To deal with dependency issue and feedback problems, the traditional ANP with an assumption of each cluster has equal weight is not reasonable. Therefore, the utilization of combining DEMATEL and ANP (DANP) can overcome this limitation. Therefore, DANP technique is used in this study to determine the influential weights of each cluster for building a network relationship map called Influential Network Relations Map (INRM). The results of DANP can contribute INRM for understanding the interaction and interdependency among the dimensions and variables. Therefore, INRM of the GSCM factors can be constructed, by using DANP technique to measure the mutual importance of each dimension and criteria which in turn assists with the decision-making process.

The DANP technique can validate the inter-dependency among variables, and confirm the relation which reflects on the system. Besides, the survey of DEMATEL is less complicated than traditional ANP, hence it helps the respondents to get a better understanding of the questions. Since it offered fewer questions and more straightforward than conventional ANP consequently, it has reduced the time required for respondents to fill in the questionnaires.

DEMATEL Algorithm

The steps for implementation of DEMATEL are explained as follows [7]:

- **Step 1**:
  The measurement of the relationship between factors i and j is made according to the view of the respondents, scaling from 0 to 4 (no influence (0),. . ., very high influence (4)) and is specified by g_c^{ij}. Matrix $\mathbf{G} = \left[g_c^{ij}\right]_{n\times n}$ as the average amount of total individual expert's scores can be obtained as follows:

$$\mathbf{G} = \begin{bmatrix} g_c^{11} & \cdots & g_c^{1j} & .. & g_c^{1n} \\ \vdots & & \vdots & & \vdots \\ g_c^{i1} & \cdots & g_c^{ij} & .. & g_c^{in} \\ \vdots & & \vdots & & \vdots \\ g_c^{n1} & \cdots & g_c^{nj} & .. & g_c^{nn} \end{bmatrix}. \tag{13.1}$$

- **Step 2:**
  The normalized version of matrix **G** is

$$X = vG \tag{13.2}$$

where

$$v = \min\left\{\frac{1}{\max_i \sum_{j=1}^n g_c^{ij}}, \frac{1}{\max_j \sum_{i=1}^n g_c^{ij}}\right\} = \frac{1}{\max\left\{\max_i \sum_{j=1}^n g_c^{ij}, \max_j \sum_{i=1}^n g_c^{ij}\right\}}$$

- **Step 3:**
  The total-influential matrix $\mathbf{T}_c$ can be calculated as follows:

$$\mathbf{T}_c = \mathbf{X}\left(\mathbf{I} - \mathbf{X}\right)^{-1} \tag{13.3}$$

where $\mathbf{I}$ is denoted as the identity matrix, $\mathbf{X} = \left[x_c^{ij}\right]_{n \times n}$, $x_c^{ii} = 0, \forall i = 1, \ldots, n$, $0 \le x_c^{ij} \le 1$, $0 \le \sum_{j=1}^{n} x_c^{ij} \le 1$, and $0 \le \sum_{i=1}^{n} x_c^{ij} \le 1$, and at least the summation of one row or column equals one (not necessarily all). It could be granteed that $\lim_{l \to \infty} \mathbf{X}^l = [0]_{n \times n}$.

- **Step 4:**
  Calculate vector $\mathbf{s} = \left[\sum_{i=1}^{n} t_c^{ij}\right]$ and vector $\mathbf{r} = \left[\sum_{j=1}^{n} t_c^{ij}\right]$, as the column sums and the row sums of the total-influential matrix $\mathbf{T}_c = \left[t_c^{ij}\right]_{n \times n}$, respectively.

  Let $i = j$ and $i, j \in \{1, 2, \ldots, n\}$, the horizontal axis vector $(r_i + s_i)$ represents the importance of the criterion and the vertical axis vector $(r_i - s_i)$ divides the criterion into a causal group and an effect group. Therefore the total influence can be obtained according to each dimension and criterion as summarized in the following rules.

  – Criteria with $(r_i - s_i) > 0$ significantly influence the other criteria (named dispatcher criteria).
  – Criteria with $(r_i - s_i) < 0$, other criteria significantly influence them.
  – Higher values of $r_i + s_i$ cause stronger relationship and lower values of $r_i + s_i$ cause weaker contact among criteria.
  – Criteria with highest $(r_i - s_i) > 0$, concern other criteria much in comparison with other criteria (needs priority for improvement).

  INRM can be obtained by mapping the data set of $(r_i + s_i, r_i - s_i)$. Based on INRM decision makers can determine how the chosen values can be improved in each criterion and dimension. For speeding up the insignificant analysis effects in matrix $\mathbf{T}$ can be filtered, and only criteria with significant effects on matrix $\mathbf{T}$ can represent the INRM. In this study, all factors are considered as an influential criterion.

  After removing insignificant criteria, the m $(m < n)$ dimensions influential matrix $\mathbf{T}_D = \left[t_D^{ij}\right]_{m \times m}$ can be concluded as the representative of significant criterion from $\mathbf{T}_c$.

- **Step 5:**
  $\mathbf{T}_D^{nor} = [t_D^{ij}/t_D^{i}]_{m \times m}$ is the normalized matrix of total-influential matrix $\mathbf{T}_D$ where $t_D^{i} = \sum_{j=1}^{m} t_D^{ij}$, $i = 1, \ldots, m$ as sum of each row. Each row of the normalized $\mathbf{T}_D^{nor}$ is equal to one, so that $\sum_{j=1}^{m} t_D^{nor_{ij}} = 1$. Similarly, the normalized $\mathbf{T}_c$ is $\mathbf{T}_c^{nor} = [t_c^{ij}/t_c^{i}]_{m \times m}$.

- **Step 6:**
  Unweighted supermatrix $\mathbf{W}_c$ is the matrix transposed from $\mathbf{T}_c^{nor}$ and the unweighted supermatrix $\mathbf{O}_D$ is the matrix transposed from $\mathbf{T}_D^{nor}$.

- **Step 7:**
  A weighted supermatrix $\mathbf{W}_c^*$ (to improve the traditional ANP) can be derived by $\mathbf{W}_c$ and $\mathbf{O}_D$, $\mathbf{W}_c^* = \mathbf{O}_c \mathbf{W}_c$.

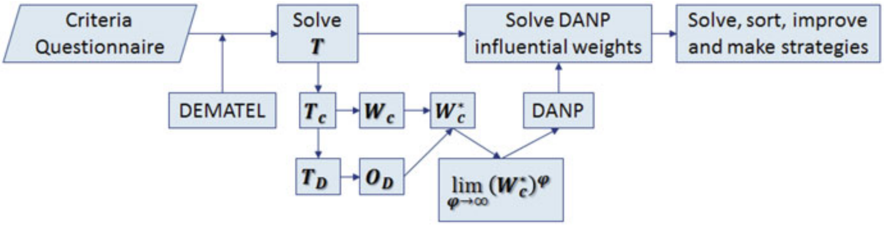

Fig. 13.2 Model procedure of DANP

- **Step 8:**
  DANP is obtained by the converges result of

$$\lim_{\varphi\to\infty} \left(\mathbf{W}_c^*\right)^\varphi,$$

as a long-term stable super-matrix.

The flowchart of proposed DANP is illustrated in Fig. 13.2.

Coal Industry in Indonesia

Coal has been known as a fossil fuel, and source of energy for electricity generation and industry. Regarding global coal reserves, Indonesia currently ranks 5th in global coal reserves according to the most recent BP Statistical Review of World Energy (https://www.bp.com). Indonesia plays a vital role in coal markets since this country is known as a regional supplier and exporters of thermal coal in Asian markets for power plants, for several years. The coal production has grown at a significant rate, and their steam coal trades are valued especially with Asian importers. It is predicted that coal prospects in Indonesia will continue to grow specially for domestic demands [18].

Although the global development is willing to replace the fossil fuel with the green energy, in Indonesia, coal will continue to be a valuable commodity for the domestic economy. Indonesias government also supports the coal usage in the power sector due to their abundant local supply and to reduce the use of expensive oil and diesel. Indonesia consumes around 20% of country's coal output while the remaining is exported. Regarding domestic consumption, about 51% is to generate electricity, and the remaining is for the industrial purpose. The use of coal in industrial sector includes cement and ceramics, pulp and paper, iron and steel, also textiles and food. The growth of coal mining in Indonesia will drive this country's economic but at the same time, the country is facing more challenges due to unfavorable characteristics of coal. In the future, Indonesia can be labeled as the most polluting energy source due to its high proportion of carbon which is

Table 13.1 Questionnaire I

Criteria	Level of importance Considering the importance of A, fill in 0–10 (11 scales) Very unimportant Unimportant Fair Important Very important 0 1 2 3 4 5 6 7 8 9 10
1.1 "Market forces"	
1.2 "Policy & regulations"	
1.3 "Internal factors"	
1.4 "Marketing & PR"	
2.1 "Waste reduction"	
2.2 "ISO14001 certification"	
2.3 "Eco-design"	
2.4 "Pollution prevention"	
3.1 "Operational"	
3.2 "Economic"	
3.3 "Environmental"	
3.4 "Social"	

concerning safety and environmental issues. Environmental association typically from developed countries with their emphasis on greener and environmentally program will bring out tighter policy and regulations.

To develop a theoretical framework for GSCM in coal industry of Indonesia, this study layouts the objective of determining the important criteria and enabling conditions for GSCM. The data was gathered through a questionnaire survey distributed among coal industry-related companies in Indonesia. In total 35 companies were surveyed across a broad spectrum of industries, including distribution, the manufacturing sector, power generation, sales, and service provider. DANP technique has been applied to pattern critical connections among criteria and dimensions and to build an INRM (Table 13.1).

The questionnaire was asked experts to define the significance of the connections among the criteria (Table 13.2). The average score of 35 questionnaires builds up the matrix $\mathbf{G}_{12\times12}$. Follow by computing the normalized direct-relation matrix $\mathbf{X}$, and total influence matrix T_D and T_c, the INRM of relationships among the dimensions are evoked as shown in Fig. 13.3.

The general finding results interpretation and criteria are summarized in Table 13.3.

Future Research Direction

- **Area 1**: In SC networks, suppliers always try to avoid the buyers' audit. Answering this question "How can buyers prompt suppliers to use more exceptional

Table 13.2 Comparison of the impact of the 12 criteria

Please fill out the compared level of 12 criteria in the following table (0. No impact; 1. Low impact; 2. Medium impact; 3. High impact; 4. Very high impact)

Dimensions	1.1 “Market forces”	1.2 “Policy & regulations”	1.3 “Internal factors”	1.4 “Marketing & PR”	2.1 “Waste reduction”	2.2 “ISO14001 certification”	2.3 “Eco-design”	2.4 “Pollution prevention”	3.1 “Operational”	3.2 “Economic”	3.3 “Environmental”	3.4 “Social”
1.1 “Market forces”												
1.2 “Policy & regulations”												
1.3 “Internal factors”												
1.4 “Marketing & PR”												
2.1 “Waste reduction”												
2.2 “ISO14001 certification”												
2.3 “Eco-design”												
2.4 “Pollution prevention”												
3.1 “Operational”												
3.2 “Economic”												
3.3 “Environmental”												
3.4 “Social”												

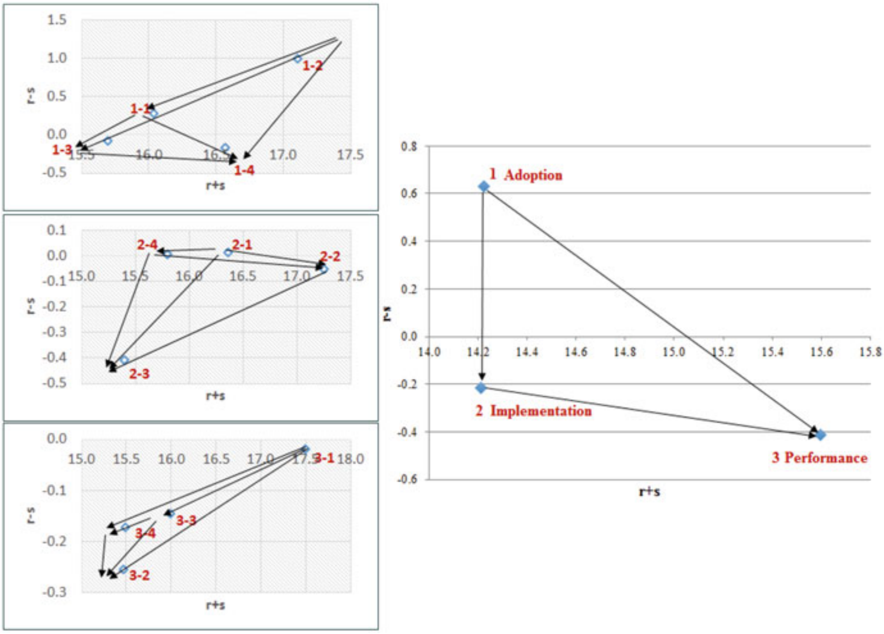

Fig. 13.3 Influential network relations map (INRM)

responsibility to check environmental impact?" opens a new avenue of research. Buyers can control the suppliers' marginal benefits by price reduction or rising salaries for operators which makes the supplier exercise more outstanding care to sustainability issues. Moreover, buyers would like to develop a necessary and sufficient condition for suppliers to avoid hiding information from the auditor. Punishing a supplier for hurting operators or the environment, or for trying to deceive an auditor, and increasing auditing, broadcasting negative audit reports, and giving loans to suppliers motivate them to sustainability. Game theory models such as negotiation and bargaining can be applied for modeling buyer–supplier motivation for environmental and social responsibility in SC contracting.

- **Area 2**: Developing smart Decision Support System (DSS) in sustainability assessment of sustainable interdependent networks. Moreover, group DSS combines communication, computing, and decision maker to formulate and solve unstructured problems by a group of people for sustainability issues in multiplex networks. Developing mathematical models of group decision making integrated with DSS would be a direction for more research in sustainable interdependent networks.

Table 13.3 INRM results and findings for the case study

Panel	Finding
General	Performance is the first in the index of strength of influence given and received ($r_3 + s_3 = 15.598$), factors of adoption ($r_1 + s_1 = 14.223$) is next, and implementation of GSC ($r_2 + s_2 = 14.214$) is the third
	There is a causal relationship between the three factors (adoption, implementation, performance)
	Factors of adoption exhibit a positive influence on the implementation and performance. Implementation of GSC has a positive influence on performance
Performance	Operational (3–1) is the first in terms of the index of strength of influence given received, environmental (3–3) is next, and social (3–4) is the third
	All criteria have $(r_i - s_i) < 0$, it shows that these criteria are influenced by other criteria
Implementation	Waste reduction (2–1) is the first in terms of index of strength of influence given and received, pollution prevention (2–4) is next, and ISO 14001 certification (2–2) is the third
Adoption	Policy & regulations (1–2) is the first in terms of the index of strength of influence given and received, market forces (1–1) is next, and marketing & public relations (1–3) is the third
All	Operational (3–1) is the most important consideration ($r_{3-1} + s_{3-1} = 17.5$) in total sum; eco-design (2–3) is the criteria with the least impact on the other criteria ($r_{2-3} + s_{2-3} = 15.4$) in total sum
	Policy & regulations has the greatest direct impact on others ($r_{1-2} - s_{1-2} = 0.993$) in total difference; eco-design (2–3) is the most easily influenced by other criteria ($r_{2-3} - s_{2-3} = -0.407$) in total difference

- **Area 3**: Using cooperative and noncooperative multi-level programming is a generalized future research direction in control and optimization of collaborative systems in sustainable interdependent networks.
- **Area 4**: Developing scenario analysis models for sustainability implications in the context of the circular economy for interconnected networks as a system of systems.

Summary and Conclusion

In this research, we proposed an analytical structure for GSCM with A.I.P criteria and implemented in the coal power generator industry in Indonesian to verify our methodology. This study practiced the hybrid DANP method to create INRM and substantial weights of criteria. Realizing corresponding weights of the dimensions and criteria for evaluation is important, and our work benefits investors and managers using GSCM to consider the most significant criteria for business.

The result of the case study shows that the most critical and least dimensions to be concerned are performance and adaptation factors. However, adoption factors are the “boost” for a business enterprise using GSCM. Consequently, without internal or external needs for sustainability practice, SC might not realize it. Adoption factors have a positive influence on GSCM development through green SC implementation. Additionally, green practice in SC affects the performance positively which is the critical factor for a successful company even using GSCM. Refer to [2, 11, 24] for more literature on GSCM in coal industry.

Appendix

Executive Summary

The chapter is divided into six sections (Fig. 13.4). The first section addresses the new and rapidly growing attention to the GSCM. Other topics include the history of sustainability intention; Definition of sustainability; International attention to sustainable manufacturing and services; Influential factors on a sustainable organization.

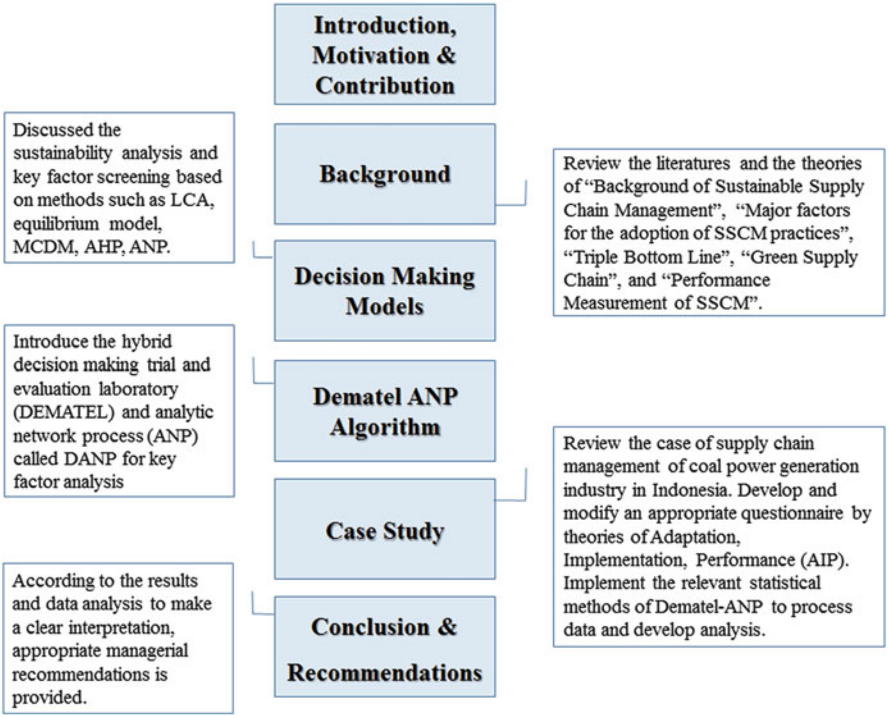

Fig. 13.4 Overview flowchart of the chapter

The second section reviews the background of GSCM. The adoption, implementation, and performance factors for GSCM are discussed with their related contents in this section.

The third section discussed the sustainability analysis and key factor screening. The discussed methods are including life-cycle assessment, equilibrium model, multi-criteria decision making, analytical hierarchy process, analytic network process, decision-making trial and evaluation laboratory, and influential network relations map.

The fourth part focuses on models and applications of proposed hybrid decision-making trial and evaluation laboratory (DEMATEL) and analytic network process (ANP) called DANP on coal power generation industry in Indonesia as the case study.

The fifth section reviews the development and future trend of GSCM for smart management such as implications for motivating supplier social and environmental responsibility.

Finally, in the last section from the gap in the literature, we propose some managerial suggestions, for who are interested in walking into the field of GSCM. The study will be concluded by providing recommendations for further research and align our mindset for the next step.

References

1. Bayazit, O., & Karpak, B. (2007). An analytical network process-based framework for successful total quality management (TQM): An assessment of Turkish manufacturing industry readiness. *International Journal of Production Economics, 105*(1), 79–96.
2. Biswal, J. N., Muduli, K., & Satapathy, S. (2017). Critical analysis of drivers and barriers of sustainable supply chain management in Indian thermal sector. *International Journal of Procurement Management, 10*(4), 411–430.
3. Bowen, F. E., Cousins, P. D., Lamming, R. C., & Farukt, A. C. (2001). The role of supply management capabilities in green supply. *Production and operations management, 10*(2), 174–189.
4. Brundtland, G., Khalid, M., Agnelli, S., Al-Athel, S., Chidzero, B., Fadika, L., et al. (1987). Our common future (\'brundtland report\').
5. Carroll, A. B. (2016). Carrolls pyramid of CSR: Taking another look. *International Journal of Corporate Social Responsibility, 1*(1), 3.
6. Carter, C. R., & Rogers, D. S. (2008). A framework of sustainable supply chain management: Moving toward new theory. *International Journal of Physical Distribution & Logistics Management, 38*(5), 360–387.
7. Chiu, W. Y., Tzeng, G. H., & Li, H. L. (2013). A new hybrid MCDM model combining DANP with VIKOR to improve e-store business. *Knowledge-Based Systems, 37*, 48–61.
8. Department of the Environment, Heritage and Local Government (2007). National climate change strategy, 2007–2012. Ireland. Website: https://www.teagasc.ie/media/website/crops/crops/NationalClimateChangeStrategy2007_2012.pdf.
9. Elkington, J. (2013). Enter the triple bottom line. In *The triple bottom line* (pp. 23–38). London: Routledge.
10. Fang, C., & Zhang, J. (2018). Performance of green supply chain management: A systematic review and meta analysis. *Journal of Cleaner Production, 183*, 1064–1081.

11. Firoz, F., Biswal, J. N., & Satapathy, S. (2018). Supplier selection criteria for sustainable supply chain management in thermal power plant. In *IOP Conference Series: Materials Science and Engineering* (Vol. 310, p. 012016). Bristol: IOP Publishing.
12. Guinée, J. B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The International Journal of Life Cycle Assessment, 7*(5), 311.
13. Handfield, R., Walton, S. V., Sroufe, R., & Melnyk, S. A. (2002). Applying environmental criteria to supplier assessment: A study in the application of the analytical hierarchy process. *European Journal of Operational Research, 141*(1), 70–87.
14. Hassini, E., Surti, C., & Searcy, C. (2012). A literature review and a case study of sustainable supply chains with a focus on metrics. *International Journal of Production Economics, 140*(1), 69–82.
15. Hsu, C. W., & Hu, A. H. (2009). Applying hazardous substance management to supplier selection using analytic network process. *Journal of Cleaner Production, 17*(2), 255–264.
16. Hsu, C. W., Kuo, T. C., Chen, S. H., & Hu, A. H. (2013). Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management. *Journal of Cleaner Production, 56*, 164–172.
17. Jeng, D. J. F., & Tzeng, G. H. (2012). Social influence on the use of clinical decision support systems: Revisiting the unified theory of acceptance and use of technology by the fuzzy DEMATEL technique. *Computers & Industrial Engineering, 62*(3), 819–828.
18. Lucarelli, B. (2010). The history and future of Indonesias coal industry: Impact of politics and regulatory framework on industry structure and performance. In *Program on Energy and Sustainable Development*. Freeman Spogli Institute for International Studies, Stanford University, Stanford. Retrieved May 10, 2011.
19. Nagurney, A., Dong, J., & Zhang, D. (2002). A supply chain network equilibrium model. *Transportation Research Part E: Logistics and Transportation Review, 38*(5), 281–303.
20. Pohekar, S., & Ramachandran, M. (2004). Application of multi-criteria decision making to sustainable energy planning—A review. *Renewable and Sustainable Energy Reviews, 8*(4), 365–381.
21. Savitz, A. (2013). *The triple bottom line: How today's best-run companies are achieving economic, social and environmental success-and how you can too*. New York: Wiley.
22. Seuring, S. (2013). A review of modeling approaches for sustainable supply chain management. *Decision Support Systems, 54*(4), 1513–1520.
23. Tate, W. L., Ellram, L. M., & Kirchoff, J. F. (2010). Corporate social responsibility reports: A thematic analysis related to supply chain management. *Journal of Supply Chain Management, 46*(1), 19–44.
24. Wu, J. Z., Santoso, C. H., & Roan, J. (2017). Key factors for truly sustainable supply chain management: An investigation of the coal industry in Indonesia. *The International Journal of Logistics Management, 28*(4), 1196–1217.
25. Zhang, M., Tse, Y. K., Doherty, B., Li, S., & Akhtar, P. (2018). Sustainable supply chain management: Confirmation of a higher-order model. *Resources, Conservation and Recycling, 128*, 206–221.
26. Zhu, Q., & Sarkis, J. (2004). Relationships between operational practices and performance among early adopters of green supply chain management practices in Chinese manufacturing enterprises. *Journal of Operations Management, 22*(3), 265–289.
27. Zhu, Q., Sarkis, J., & Lai, K. (2012). Green supply chain management innovation diffusion and its relationship to organizational improvement: An ecological modernization perspective. *Journal of Engineering and Technology Management, 29*(1), 168–185.
28. Zhu, Q., Sarkis, J., & Lai, K. (2013). Institutional-based antecedents and performance outcomes of internal and external green supply chain management practices. *Journal of Purchasing and Supply Management, 19*(2), 106–117.

Chapter 14
Protection Schemes for Sustainable Microgrids

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Nomenclature

AB, BC, CA	Line-to-line fault
ABG, BCG, CAG	Double line to ground fault
AG, BG, CG	Single phase to ground fault
cf	Chopping fraction
df/dt	Rate of change of frequency
f	System frequency
$f(k)$	Frequency at any instant k
f_{osc}	Oscillation frequency
H	Generator inertia constant
G	Rated capacity of generator
i_A, i_B, i_C	Currents in phases A, B, and C, respectively
I_0, I_1, I_2	Zero sequence, positive sequence, and negative sequence current
I_h	hth harmonic component of current
n	Sampling instant
$P_{mismatch}$, $Q_{mismatch}$	Active and reactive power mismatch between main grid and DG
P_{load}, Q_{load}	Active and reactive power of the load
P_{DG}, Q_{DG}	Active and reactive power generated by DG
tx	Length of measuring window
t_z	Zero time or dead zone
T_{vutil}	Time period of grid voltage
v_A, v_B, v_C	Voltages of phases A, B, and C, respectively
V_0, V_1, V_2	Zero sequence, positive sequence, and negative sequence voltage
ΔP_{DG}	Change in output power at DG side

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$\Delta\omega_k$	Error in frequency
ϕ_i	Phase angle of current at DG end
ϕ_v	Phase angle of voltage at DG end
ω_k	Frequency in *k*th cycle

Introduction

Overview

The significant benefits associated with sustainable microgrids have led to high efforts to expand their inclusion in the electric distribution system. Even with multiple advantages and large acknowledgement, the design, control, operation, and protection issues cannot be avoided. The dependency of transmission and distribution operators is increasing to a greater extent. The two different operating modes of microgrid are grid-connected mode and islanding mode. In both the operating modes the secure operation of protective algorithm is most desirable. In microgrid, the involvement of converter-interfaced renewable distributed generations (DGs), such as photovoltaic (PV) DGs, introduces nonlinearity. This is another major concern for the relaying system. During fault, the infeed current from DG end is very less due to which protective relay is unable to consider the situation as an abnormal phenomenon. The traditional protection schemes employed for protection of radial distribution networks may fail to operate with the inclusion of DGs. Islanding detection, relay coordination, fault detection, and fault classification are the well-known protection issues with microgrid. Hence, this chapter presents a relook to basic concepts and importance of sustainable microgrids, and examines the envisaged protection issues and protection strategies concerned with the integration of these networks. Performance of various techniques in terms of merits and demerits has been discussed which may provide future direction for research to design a reliable protection scheme for these networks.

General Introduction

Power system currently undergoes considerable change in operating conditions due to large diversion in generation side and mainly inclusion of large number of distributed energy resources (DER). The DER is a combination of different power generation technology in small or microscale. Large generators are being replaced by several smaller DERs [1]. At present, the optimal operation of such complex networks is becoming a prominent issue. The introduced interdependent networks cause problems in optimization and increase computational burden. Moreover, with the presence of large number of nodes, failure of few nodes may have a devastating effect on system [2].

The micro resources such as solar, wind, and hydro are generally integrated in the distribution level so as to reduce transmission loss and cost. Moreover, the high percentage of power disturbance at low-voltage end will be reduced. Such a system although connected to high-voltage level grid but energy storage devices are facilitated at the distribution level so that during islanding mode uninterrupted power supply can be provided to the end users. So, in a simple meaning an independent grid driven by small-scale energy resources and capable of providing uninterrupted power supply to end user in case of islanding from the main supply grid is known as microgrid. Microgrid can also be defined as an integrated energy system consisting of DER, multiple electrical loads, and energy storage devices operating as a single, autonomous grid which can operate either parallel to or islanded from the existing utility power grid.

Microgrids are emerging as an important part of power distribution system due to significant developments in distributed generation (DG) technology. It enables the use of renewable energy sources such as photovoltaic cells, fuel cells, and wind power as a solution to the problems of greenhouse gas, growing energy demand, and depletion of conventional fossil fuel-based energy sources. The presence of distributed generation system (DGs) close to the loads makes the power delivery more reliable as it reduces power transmission loss and helps to improve the energy efficiency of the power system. A microgrid has the ability to operate independently in islanded mode in case there is any disturbance in the utility grid such as voltage fluctuation and frequency deviation. It can supply the critical loads while operating independently in islanded mode. The resiliency of the grid is improved in a sustainable manner by employing certain decentralized techniques [3]. The size of a typical microgrid is about 1 MVA capacity and it often provides both heat and electricity to the consumers. A typical microgrid layout is shown in Fig. 14.1. In this figure, the microgrid is connected with the medium-voltage (MV) system through a breaker. The control through breaker is necessary because in case of any failure or maintenance work required in MV grid, the microgrid can operate independently.

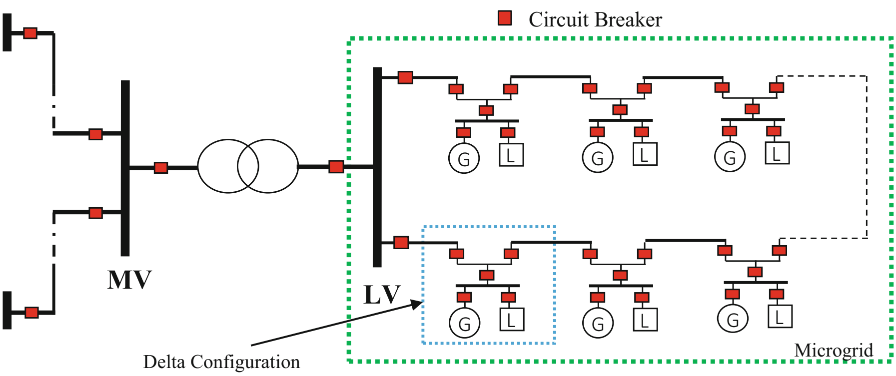


Fig. 14.1 Layout of a typical microgrid. *MV* medium voltage, *LV* low voltage

Such a configured microgrid can also be interlinked with other low-voltage grids at the end points. Improved efficiency and reliability, environmental friendly, improved service quality, uninterrupted power supply, and lower energy consumption are the common advantages offered by microgrid. However, the use of various types of DGs for power generation presents a challenge for operating, controlling, integrating, and protecting the microgrid.

Protection Issues with Microgrid

Protection system is an important part of power system while talking about reliable and healthy operation of the same. The design of microgrid system is incomplete without the fulfillment of different important features of protection system such as selectivity, sensitivity, security, dependability, speed, and cost. Since microgrid systems are connected to both main grid and DER, the nature of fault developed will be different and it is the job of the protection system to respond to each and every abnormal situation correctly. For any fault in main grid, the protection system should isolate the same part from the microgrid in order to avoid power interruption. Again, after fault clearance, some of the load should be disconnected so that stability will be maintained between load demand and generation. This job can take place by adaptive logics to avoid unwanted operation. However, this may not be true every time. False detection, unwanted relay operation, and improper islanding detection can worsen the system healthy operation. In this case, the selectivity, sensitivity, dependability, and security issues arise. In a broader sense, the different protection issues associated with microgrid systems are islanding detection, overcurrent relay coordination, fault detection, and classification. Each issue is considered separately and described in the next subsections.

Islanding Detection

Conventional distribution systems are passive networks where power is supplied to the distribution level from the transmission systems. The concept of DG is introduced to exploit the advantage of renewable power generation and extended to distribution level. Today's systems incorporated with multiple distributed generation systems can be operated by connecting them to power grid as well as in islanded mode [4]. Islanding is a condition where main source is disconnected from the microgrid. The islanding can be intentional or nonintentional. The salient feature of a microgrid is its ability to operate in islanded mode by isolation from the main grid through the point of common coupling (PCC). Islanding can be introduced for either economic or reliability purpose. During utility grid disturbances, microgrid is converted from grid-connected mode to islanded mode. This will allow the end users to avail uninterrupted power supply from the DERs. During such a condition, the voltage and frequency would be controlled by the master controller in microgrid. Once the disturbance is removed, the islanded microgrid would be again synchronized with the utility grid.

Once a utility grid interconnected with a microgrid the total power demand is supplied through both the sides. Failure or isolation of any generating unit leads to mismatch between supply and demand. In the case of power mismatch, the islanding detection is a challenging task. At zero mismatch the detection is difficult and the percentage of true detection increases for higher end mismatch. In distribution system capacitor bank is provided to improve the voltage profile. The switching of capacitor bank is another major concern for many islanding detection schemes.

Overcurrent Relay Coordination

The reason behind relay coordination is to maintain the selectivity among different protective devices located at different sections involved to protect several faults for the safe and healthy operation of power system. In an efficient and coordinated protection system, faults are eliminated in the minimum possible time, isolating the smallest part of the system containing the cause of fault. This is achieved easily in a radial distribution network with only one power flow direction because the fault current magnitude reduces along with feeder, and hence relay coordination is possible.

However, once a microgrid is formed, the topology and characteristics are very much different from the traditional radial distribution network. The microgrid can be operated either in grid-connected mode or in islanded mode. In both the operating modes and due to the involvement of DG system, the current level during fault or the power flow direction may vary which is a major concern for the secured microgrid operation. Any conventional protection scheme such as nondirectional overcurrent relay, fuse, and recloser needs proper coordination while applied to such a network. During both the operating modes, the infeed will be different and relay coordination is a major concern. Also, bidirectional power can cause maloperation of protective relay. Thus, dependence on overcurrent relays without direction-sensitive capability becomes inadequate and new strategy must be investigated to secure the microgrid operation. Integrated logic-based adaptive protection can provide secured protection. However, the proper coordination between the different logic is also essential for the successful microgrid operation.

Fault Detection and Classification

Detection and classification of different faults in microgrid system is a very crucial task due to wide variation in fault current magnitude both in grid-connected and islanded modes. When extensive number of small distributed energy resources employing synchronous or induction generator units is associated with distribution network or utility grid, fault current level is modified as both the category of generators will contribute to fault current. Distributed generation source employing inverters has lower fault current contribution than synchronous machine DGs. As fault current level does not vary more as compared to load current, some of the relays will operate with time delay whereas others will not trip. The unidentified fault may proliferate throughout the system and can cause damage to the equipment.

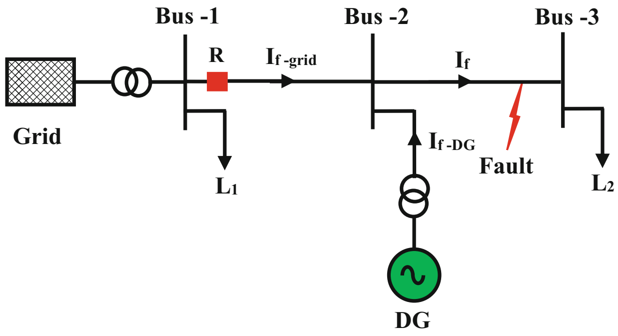


Fig. 14.2 Variation in fault current level due to incorporation of DG

Suppose a fault has occurred at downstream of point of common coupling, fault current contribution will be by both the utility and DG. Relay placed at upstream of DG measures fault current supplied by upstream source. From Fig. 14.2 it is inferred that during a fault between bus 2 and bus 3, relay will measure the fault current supplied by main grid only. However, the original fault current value is different. Hence, relay may mis-detect the fault. Occurrence of short circuit faults may have impact on magnitude, direction, and duration of fault currents.

Background

In the past few years, new developments of protection logic to mitigate the protection issues of microgrid have been done. The three major protection issues with microgrid are islanding detection, relay coordination, and fault detection and classification. The different possible protection solutions for the aforementioned issues are discussed below.

Protection Solutions for Islanding Detection

Islanding is a phenomenon that occurs when a part of distribution network becomes isolated electrically from the remainder of the power system and yet is continuously powered by distributed generators [5]. The contemporary action is to isolate all the DG units as soon as islanding condition occurs [6, 7]. Islanding can be intentional (preplanned) or unintentional (accidental) based on their occurrence. Creating an island intentionally for load shedding and maintenance purpose is referred to as intentional islanding whereas unintentional islanding occurs due to inception of fault or failure of equipment. Unintentional islanding gives rise to major issues which include:

1. Maintenance of voltage and frequency within standard acceptable limits
2. Hazard to line worker security by DG units feeding the loads
3. Out-of-phase reclosure of DG unit as a result of instantaneous reclosing

Hence, detection of occurrence of island is very essential in power system. Various techniques have been developed to detect islanding. In the following subsections, the details of these methods are explained and evaluated.

Remote Techniques

Remote islanding detection methods are based on transmission of data between the DG and main grid through a proper communication channel. Communication channel sends a trip signal to DG as soon as the islanding event is detected. Power line carrier communication (PLCC) and supervisory control and data acquisition system (SCADA) are employed for detection of island. Figure 14.3 shows the basic operation of remote islanding detection technique. It is recognizable from the figure that at grid side transmitters are installed whereas receivers are installed at all DG ends. The communication signal is produced and is sent through a PLCC system [8, 9]. There will be continuous reception of signals by receiver during normal operation when the main grid is connected to microgrid. When the microgrid is islanded, reception of signal is interrupted; that is, receiver will not receive any signal as the PLCC communication channel is collapsed.

SCADA is also used as a medium for communication between grid and DGs [10–12]. Status of all the reclosures and CBs is monitored through SCADA system. This type of scheme is also known as transfer trip scheme. This scheme requires all the CBs to be monitored and should be directly linked with the central substation SCADA system. When islanding is detected a signal will be sent to all DGs to discontinue its operation.

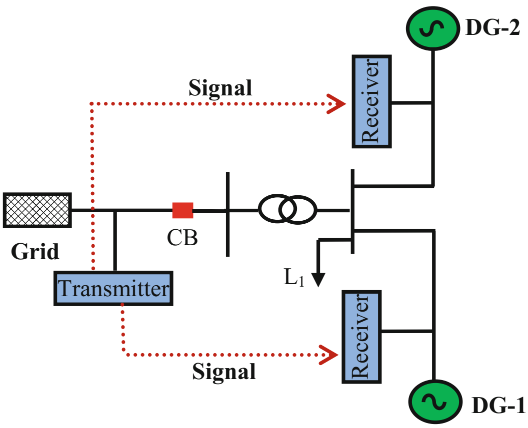


Fig. 14.3 Basic operation of remote islanding detection method

Remote techniques are reliable and have negligible non-detection zone (NDZ) but are uneconomical and complicated for small distribution system. Further, this technique is dependent on communication medium. So, failure in communication medium will result in maloperation of relays throughout the system. Hence, local islanding detection techniques are highly preferred over remote islanding detection techniques.

Local Islanding Detection Techniques

Local techniques are based on the measurement of parameters such as voltage, current, frequency, power, and harmonic distortion at DG terminal. Local techniques are further classified into active, passive, and hybrid technique. Some of the available passive and active techniques are mentioned below.

Passive Techniques

Passive islanding detection techniques utilize evaluation of system parameters such as frequency, voltage, current, and power at point of common coupling (PCC) or at terminals of DG. There is a huge variation in these parameters when islanding occurs. Figure 14.4 shows the basic operation of passive islanding detection technique. Variation in parameters is compared with the stipulated threshold setting for detection of islanding condition. Few of the commonly used passive islanding detection techniques are discussed in the following section.

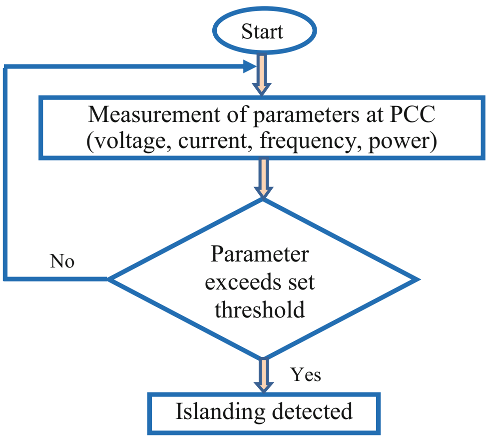


Fig. 14.4 Basic operation of passive islanding detection technique

1. Under/overvoltage (UV/OV) and under/overfrequency (UF/OF)

   This technique is based on the measurement of grid voltage and frequency at DG terminals and continuously monitoring these parameters to check whether it lies within the limits as defined by relevant standards [13]. The technique is widely implemented with photovoltaic inverters. If the limits for voltage and frequency at inverter terminal are violated, inverter will be disconnected from grid supply. During islanding there is power mismatch between the load (P_{load}, Q_{load}) and generation (P_{DG}, Q_{DG}) and is given by

$$\begin{aligned} P_{\text{mismatch}} &= P_{\text{load}} - P_{\text{DG}} \\ Q_{\text{mismatch}} &= Q_{\text{load}} - Q_{\text{DG}} \end{aligned} \tag{14.1}$$

   where P_{mismatch} and Q_{mismatch} represent the active and reactive power mismatch between main grid and DG, respectively. This difference in power is supplied by the grid when DGs are connected with the main grid supply. During islanding, in order to achieve balance in active and reactive power flow voltage and frequency deviate from the nominal values at the DG terminal.This method is economical and it does not affect power quality of the system. But, it has large non-detection zone. To reduce the NDZ of this technique, a method is proposed in [14] by comparing the P-V and P-Q characteristics of the constant current controlled inverters.

2. Rate of change of frequency (ROCOF)

   It is the conventional method used for detection of islanding condition. Whenever DG is islanded from the main utility, frequency variation occurs due to the active power mismatch between grid and DG [15, 16]. The rate of change of frequency (ROCOF) is computed using generator swing equation and is given by

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\Delta P_{\text{DG}}}{2H \times G} \times f \tag{14.2}$$

ΔP_{DG} = change in output power at distributed generation side.
H = generator inertia constant.
G = rated capacity of generator.
f = system frequency.
This change in frequency ($\mathrm{d}f/\mathrm{d}t$) is integrated over few cycles, usually 2–50 cycles, and if it exceeds a predefined threshold ROCOF relay operates/trips. This method is commonly utilized as it is easy and simple to implement. It provides speedy detection of islanding as compared to overvoltage/overfrequency protection. The main demerit of this algorithm is that it maloperates when there is low power mismatch (less than 15%) between grid and DG [17].

3. Voltage phase jump detection

   Phase jump detection (PJD) is based on monitoring the difference in phase angle between the terminal voltage of inverter and its output current to detect abrupt jump [18]. During normal operation, the current at inverter terminal is synchronized with the PCC voltage. When islanding occurs, there is no change in output current of the inverter, but PCC voltage will jump to a new phase to exhibit the same load phase angle. As a result, there is an abrupt "jump" in PCC voltage. If this difference in phase exceeds the set threshold, islanding is confirmed.

This method provides fast detection of islanding within 10–20 ms [19], though load switching causes difficulty in selection of threshold.

4. Voltage unbalance and harmonics measurement

Unbalance in voltage arises due to the change in network topology and loading for DG during islanding [20]. Voltage unbalance is given by the following equation:

$$\mathrm{VU}_t = \frac{\mathrm{NSV}_t}{\mathrm{PSV}_t} \times 100\% \tag{14.3}$$

where NSV_t and PSV_t are the amplitudes of negative sequence and positive sequence voltage at time t. The unbalance in DG terminal voltage is continuously monitored and is compared with the set threshold for the detection of island. As negative sequence voltage is extracted for computing voltage unbalance which is influenced by harmonics, it causes difficulty in selecting threshold.Variation in harmonics occurs due to the change in loading of DG, when it is disconnected from the main supply [21]. The change in total harmonic distortion (THD) of current at time t is given by

$$\mathrm{THD}_t = \frac{\sqrt{\sum_{h=2}^{\infty} (I_h)^2}}{I_1} \times 100 \tag{14.4}$$

where h is the harmonic component. If the change in THD exceeds the threshold, islanding is detected. In [22], it is illustrated that there is significant increase in third harmonic of DG end voltage due to magnetic hysteresis characteristics of transformers.A combined technique employing voltage unbalance and total harmonic distortion of current is implemented in [23] for islanding detection. Implementation of this technique is troublesome due to selection of two thresholds.

5. Rate of change of power output (ROCOP)

This method observes the change in power at target DG terminal, as disconnection of grid from DG produces change in load [24] and this change will be much higher in islanded system than in non-islanded system. The change is integrated over a predefined interval and as soon as it exceeds the threshold value, islanding situation is detected.

$$\sum_{n=-tx}^{n=0} (\Delta P_{\mathrm{DG}})_n > K_s \tag{14.5}$$

where ΔP_{DG} is change in active power at DG end, n represents sampling instant, length of measuring window is represented by tx, and K_s is predefined threshold. The major advantage of this technique is its ability to detect unsynchronized reconnection of the grid supply to the DG unit.

6. Rate of change of frequency over power (ROCOFOP)

   This technique monitors the rate of change of d*f*/d$P_{L,}$ as a detection index for identifying islanding condition [25]. P_L indicates the load power. The performance of this technique is better than ROCOF relay as it works satisfactorily for lower end power mismatch. Threshold setting may be quite difficult because two predefined threshold settings need to be given for the implementation of this method.

7. Rate of change of phase angle difference (ROCPAD)

   ROCPAD technique estimates the phase angle of current and voltage signals at DG terminal and then computes the phase angle difference between voltage and current signals [26]. Islanding is detected if the rate of change of phase angle difference exceeds predefined threshold. The technique is compared with ROCOF and is found to be effective even with zero active power mismatch condition during islanding:

$$\text{ROCPAD} = \frac{\Delta\left(\phi_v - \phi_i\right)}{\Delta t} \tag{14.6}$$

ϕ_v = phase angle of voltage at DG end.
ϕ_i = phase angle of current at DG end.

8. Oscillation frequency estimation

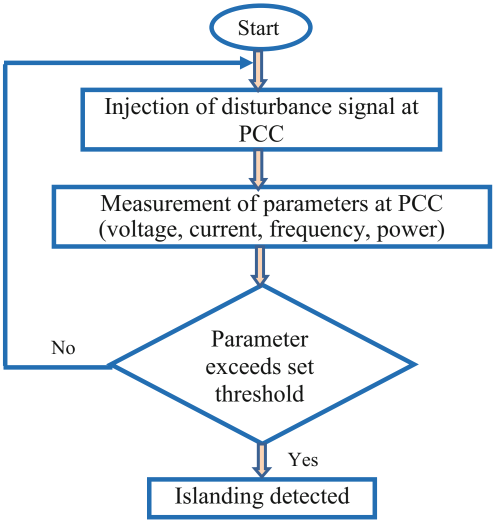
   This method is based on the estimation of frequency of oscillation of synchronous machine, to detect islanding events. Estimation of oscillation frequency is done using very small window of 2.1 ms (16 samples), to have rapid islanding detection [27]:

$$f_{\text{osc}}(k) = \frac{f_{\text{sampl}}}{2\pi N} a\ \cos\left(\frac{f(k) + f(k-2N) - 2f_o}{2f(k-N) - 2f_o}\right) \tag{14.7}$$

f_{sampl} represents sampling frequency, system frequency is represented by f_o, $f(k)$ is the frequency at any instant k, and N indicates the half window size and is equal to 8. As compared to ROCOF, this technique is sensitive to different events and detection time is less than 40 ms.

From the aforementioned techniques, it is observed that the major drawback of passive techniques is the large NDZ, which fails to detect the islanding condition. Loading near distributed generation affects the performance of passive islanding detection technique. These shortcomings can be overcome by implementation of active techniques, which are illustrated in following section.

Fig. 14.5 Basic operation of active islanding detection technique



Active Techniques

Active techniques are recently implemented by injecting small disturbances into the grids and then studying its effect on different system parameters including voltage, current, power, frequency, and impedance. These methods are very effective for lower end active and reactive power mismatch but the injection of disturbance creates deterioration of power quality in the system which is obnoxious for consumers and the utility grid. Figure 14.5 shows the operation of power flow in active islanding detection. Various active islanding detection techniques are described in the following section.

1. Active frequency drift (AFD)

    This method is implemented for photovoltaic systems. It utilizes inverter output current waveform which is injected to utility grid by PV inverter. The current waveform is slightly distorted by inserting zero-time zone or dead zone in every half cycle. When islanding occurs, due to distortion of injected inverter current the frequency of voltage waveform will deviate up and down leading to the phase error between inverter output current and voltage waveform. Hence, inverter output frequency is also deviated to eradicate the phase error. This frequency deviates until the overfrequency/underfrequency relay is tripped.

    The distortion in inverter output current is illustrated by a parameter known as chopping fraction "cf" [28, 29] and is given by the following equation:

$$\mathrm{cf} = \frac{2t_z}{T_{\mathrm{vutil}}} \tag{14.8}$$

t_z = zero time or dead zone.
T_{vutil} = time period of grid voltage.

AFD method implementation is simple and works effectively with pure resistive load and detects islanding within 2 s [29, 30]. When load is non-resistive, its NDZ increases. The effectiveness of this technique reduces with multiple inverters as a consequence of different AFD for each inverter.

In order to improve the performance of AFD with multiple inverters and to reduce NDZ, AFD with positive feedback (AFDPF) [29] is utilized. A positive feedback is employed to expedite the drift in frequency by increasing "cf" as mentioned in the below equation:

$$\mathrm{cf}_k = \mathrm{cf}_{k-1} + F\,(\Delta\omega_k) \tag{14.9}$$

cf_k = chopping fraction of kth cycle.
cf_{k-1} = chopping fraction of (k−1)th cycle.
ω_k = frequency in kth cycle.
$\Delta\omega_k$ = error in frequency in kth cycle.
F = linear function.

Positive feedback employed with AFD in PV systems enlarges the drift in frequency produced by different PV inverters, hence minimizing the NDZ to a greater extent. The demerit of AFDPF is that it affects the power quality of system by introducing subharmonics into the system.

2. Sandia voltage shift (SVS)

   This technique also utilizes a positive feedback and is applied to the magnitude of PCC voltage. Hence, due to distortion in voltage, inverter output current also varies along with output power. PCC voltage is slightly distorted during steady-state operation. In islanding mode, variation in output power can expedite the drift in voltage for detection of islanding condition. Undervoltage or overvoltage protection will sense the changes in voltage and compare it with threshold. As the threshold is violated, inverter operation is ceased. The inverter controller reference current [31] is computed as

$$I_{\mathrm{ref}} = \frac{k_v \cdot \Delta V + P_{\mathrm{DG}}}{V} \tag{14.10}$$

V = PCC voltage
P_{DG} = DG output power
ΔV = change in voltage
and output current of the inverter is varied in proportion to the variation of voltage by a factor k_v.
Even though the implementation of SVS is simple it degrades the power quality of system.

3. Slip-mode frequency shift (SMS)

   It is also one of the techniques that employ positive feedback for detecting grid disconnection from microgrid. Positive feedback is implemented with the voltage phase angle at PCC and the drift in frequency is monitored to detect islanding. The phase angle of the inverter (θ_s) is set as [32, 33]

$$\theta_s = \theta_m \sin\left(\frac{\pi}{2}\frac{f_{k-1} - f}{f_m - f}\right) \tag{14.11}$$

f = system frequency.
f_{k-1} = frequency of previous cycle.
θ_m = maximum phase angle occurring at frequency f_m.
During grid-connected mode, θ_s is almost zero. After the grid disconnection θ_s and frequency vary and islanding is detected if variation in frequency crosses the threshold. This technique has smaller NDZ compared with other active islanding detection techniques and possesses high reliability by incorporating an additional phase shift [32].

4. Negative-sequence current injection

   In this technique, negative sequence current is injected into voltage source current controller [34–36]. Islanding is detected by observing the negative-sequence voltage at DG terminal. During grid-connected mode, the negative-sequence current entirely flows to main grid as the impedance of main grid is low. However during islanding injected negative-sequence current passes through the load giving rise to the positive sequence and negative sequence voltage at PCC. The percentage imbalance in voltage is given by

$$\text{VU} = \frac{V_n}{V_p} \times 100\% \tag{14.12}$$

V_n = amplitude of instantaneous negative-sequence voltage.
V_p = amplitude of instantaneous positive-sequence voltage.
VU is compared with the threshold value for islanding detection. Detection of island is carried out within 60 ms, with negative-sequence current injection of only 2–3%. It has approximately zero NDZ and the technique is not influenced by load variations.

5. Impedance measurement (IM)

   The technique is based on variation in system impedance due to islanding. During islanding variation in impedance is observed by computing dv/di seen from the inverter terminal [37]. This method is not suitable for multiple inverter cases and selecting a threshold is also difficult due to the necessity of actual magnitude of grid impedance.

   To overcome the drawback of aforementioned impedance measurement technique, negative-sequence impedance islanding detection is implemented in which small negative-sequence current is injected at different frequency levels [38]. The technique performance is valid only for small disturbances in system.

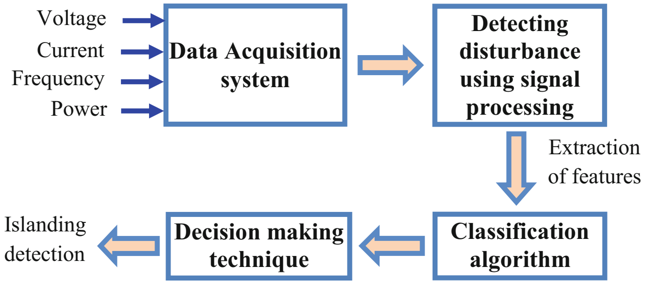


Fig. 14.6 Basic flow diagram of intelligent islanding condition classification technique

Computational Intelligence-Based Techniques for Islanding Detection

For the minimization of non-detection zone and for rapid detection of islanding, various signal processing techniques have been employed. To extract more unique and appropriate features such as energy content and standard deviation of the signal, these techniques are utilized. These extracted features can then serve as inputs to the artificial intelligent (AI) classifier to perform the classification of the islanding and non-islanding detection. Common AI classifiers used in islanding detection include the decision tree (DT), rule-based techniques, artificial neural network (ANN), probabilistic neural network (PNN), fuzzy logic (FL), and support vector machines (SVM). Figure 14.6 shows the steps involved in performing the islanding condition classification. Following are some of the techniques that use signal processing for islanding detection.

1. Wavelet Transform (WT)

   Authors of [39, 40] use time frequency detection technique based on the investigation of DG voltage, current, and power signal. Fifth decomposition level is utilized for islanding operation mode. The benefit of using this method is the reduction in number of sensors required and less computational burden.

   In [41], the sequence component of current and voltage at DG terminal are acquired and processed using wavelet transform. Change in standard deviation and energy of first-level detailed coefficient is observed for one full cycle for islanding detection. In [42], DWT is used for processing of voltage signal at DG end and in [43] detailed coefficient matrix is obtained by applying WT to voltage signal at DG end and wavelet singular entropy-based index is obtained using Shannon entropy which differentiates islanding and non-islanding events.

2. S Transform (ST)

   The modification of WT with phasor information, known as ST [44], was developed for the detection of different power quality disturbances and islanding, based on moving a varying and scalable localizing Gaussian window. Multi-resolution analysis can be done using ST and can be carried out by processing the complete phase of each frequency component which helps to give accurate detection result in the presence of noise. In [45], spectral energy content of the S contour was computed after the negative-sequence voltage and current signal were processed using ST. Similarly, in [46, 47] negative-sequence component of voltage was processed using ST. Islanding is detected by computing energy content and standard deviation of the contour. The disadvantage of using ST is that its reliability reduces with the nonstationary signals comprising of transients [48].

3. Hilbert–Huang Transform (HHT)

   HHT is a time-frequency-based technique and is a combination of empirical mode decomposition (EMD) and Hilbert transform. HHT is used for analyzing nonstationary power signals rigorously [49]. It is an extremely adaptive and accurate method for feature extraction. Various modes of signals can be extracted with variable timescale using EMD. In [50] EMD is applied to voltage at point of common coupling (PCC) to obtain the intrinsic mode functions (IMF). First IMF is used as a parameter to detect islanding. Further in [51], HHT is applied to all IMF components to have frequency, phase angle, and instantaneous amplitude information. Then, different features describing the signals are calculated including standard deviation and energy of phase angle and amplitude to discriminate islanding and non-islanding conditions.

4. Intelligent Techniques

   The data collected by extracting features of signals through signal processing technique is utilized by artificial intelligent methods such as neural networks, probabilistic neural network (PNN), support vector machines (SVM), and decision trees for detection of island. These data sets are used for training the system. Hence, computational burden and training time are high but it has a benefit of having smaller non-detection zone [52].

   In [53], voltage and current signals are measured at point of common coupling (PCC) and their instantaneous values are processed to extract autoregressive coefficients. This data set is used to train the SVM model off-line and islanding is detected. In [54, 55] probabilistic neural network (PNN) and PNN in combination with wavelet are proposed. In [56], Bayesian classifier is utilized which achieves higher accuracy but the computational burden was high. Decision tree-based classifier is implemented in [57, 58] and in [59] various intelligent techniques are compared and decision tree-based classifier is found to have the best accuracy. Then in [60], fuzzy rule-based system combined with decision tree is proposed. The technique is easy to implement and is insensitive to noise.

Protection Solutions for Relay Coordination

The selectivity between protective devices during various fault scenarios is the prime objective for coordination of protective devices in order to ensure safe operation and reliability of the power network. In distribution system primary protection as well as backup protection are given by overcurrent relays. To clear the fault in minimum possible time to isolate only the faulty section from the rest of the system, coordination among overcurrent relays is mandatory.

Conventional distribution system having radial nature protection system is designed for unidirectional power flow. However, incorporation of DER causes changes in the topology of the distribution network and flow of fault current is there in both the directions. Variation in fault current level due to two operating modes and bidirectional power flow causes complications for protection coordination as the protection schemes designed for conventional distribution network fail to operate when DER is incorporated in distribution network. To assure proper coordination among primary and backup protection, several protection strategies have been adopted employing optimization and heuristic approaches that are implemented including communication-based techniques and are reviewed in the following section.

Communication-Based Methods

In communication-based coordination techniques, measurement devices and circuit breakers are connected with central control unit through communication networks. Location of fault is determined via central control unit by monitoring voltage and current signals. Faulty portion is isolated by sending a trip signal to circuit breakers [61].

By utilizing such interconnected devices, it is possible to properly supervise the coordination between various protective devices of the whole network during both grid-connected and islanded modes of operation. Further the faulted area will be isolated rapidly enhancing the reliability of the power supply to the consumers [62].

In [63], a wide area differential protection scheme is implemented in microgrid by utilizing communication links to protect household PV systems against three phase faults. Intelligent electronic devices (IEDs) and circuit breakers at each bus are connected to the control center via wireless mobile broadband. The real -time current measurements are monitored by IEDs and the data is sent to control center. Faulted portion is identified by the control center and trip signals are issued to the circuit breakers to isolate the faulty portion.

In [64], an optical Ethernet communication network is utilized to interconnect measurement devices, circuit breakers and control units at each bus. The scheme is proposed for radial microgrid network. The scheme has fast fault clearing time, but relay may maloperate due to lack of proper communication channels.

Multi-Agent-Based Methods

Multi-agent-based technology comprises various intelligent agents that coordinate with other agents as a single unit. Basic operation of multi-agent-based protection coordination strategy is proposed in [65–67] as shown in Fig. 14.7. Individual relays

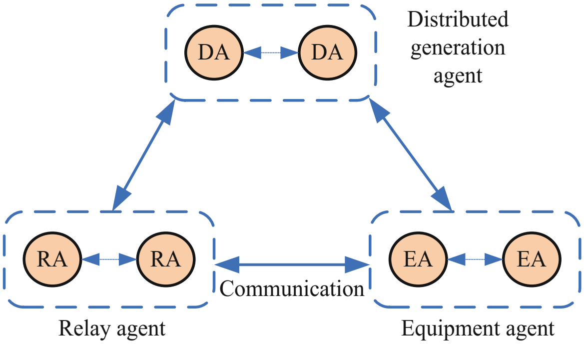


Fig. 14.7 Basic operation of multi-agent-based method

established in the system are considered as relay agent. It communicates with other agents to acquire specific information to identify relay maloperation and circuit breaker failure so as to execute backup operation for improved performances. Each DG is considered as one agent. The connection status of DG is provided to relay agent through communication between DG agents and relay agent. Elements which consist of crucial information are included under equipment agent (EA). It gathers the local system information and communicates it to relay agent for protection coordination function. All these three agents communicate among themselves to achieve efficient coordination. Java agent development (JADE)-based platform is employed for checking the effectiveness of scheme. Simulation results show that there is a successful communication of data among agents.

The scheme is capable of providing backup protection in case primary protection system fails and has the ability to self-check and self-correct. Protection using multi-agent-based method is complicated for complex network.

Expert System for Protection Coordination

Expert system-based protection performs tasks alike human experts and is characterized in terms of knowledge base, knowledge inference, and explanation. Traditional expert system deals with the protection issues utilizing information in its knowledge base and knowledge inference [68, 69]. It automatically gives clarification regarding why and how it has achieved its decision, which is utilized by user to review the efficacy of the decision, knowledge, and knowledge inference.

This aspect is essential as it authorizes the user to repeatedly upgrade the inference and information of the knowledge base. Expert system-based protection coordination in distribution system is implemented in [70]. The scheme is designed for radial distribution network and it has four modules. They are graphical user interface (GUI), engineering analysis, knowledge base, and inference engine. At first, the information regarding microgrid configuration and DGs is given as input to expert system through GUI. Load flow and short circuit analysis is carried out by engineering analysis module for formation of rule base. Next, all the information regarding distribution lines, buses, DGs, relays, fuses, and coordination data which is stored in knowledge base is sent to inference engine for proper settings of protective coordination.

Other Protection Coordination Strategies

The impact of high penetration of DG on protection coordination is illustrated in [71], and recommended an adaptive protection coordination scheme for microgrid. Effect of distributed generation on traditional protection scheme is illustrated in [72–74]. A novel adaptive non-pilot overcurrent protection coordination utilizing steady-state fault currents is implemented. A technique implementing both adaptive and nonadaptive relaying scheme is proposed in [75]. The settings of overcurrent relay which malfunction due to contribution of DG fault current are readjusted utilizing adaptive relaying scheme. Fault current from distributed energy resource is blocked by installing fault current limiters in series with DG in case of nonadaptive relaying scheme. A linear programming-based adaptive optimal coordination of overcurrent relays is discussed in [76]. The state of the system is estimated by central computer and determines whether to change the settings of relay or not. The new settings calculated by central computer are transferred to the relays through substation control computers.

In [77], to restore the fault current level to the actual level (without considering DG), fault current limiters are incorporated in series with DG and utility interconnection point. Further in [78], a technique is proposed to minimize the recloser-fuse miscoordination which occurs during various fault scenarios. The best location of DER is obtained where loss of coordination is minimum. Protection coordination technique for meshed distribution systems is proposed in [79–81] by making use of user-defined time-inverse characteristics of directional inverse time overcurrent relays. In [81], an enhanced backtracking search algorithm is implemented to optimize the operating time of relays while retaining the proper coordination among relays. The algorithm is found to be efficient as compared to particle swarm optimization, self-adaptive differential evolution, and artificial bee colony.

Protection Solutions for Fault Detection and Classification

Accurate and timely detection of faults is one of the most critical issues in the protection of microgrid due to the variation in magnitude of fault current level in both grid-connected and islanded operational modes. Magnitude of fault current depends on the type of DG unit present in the microgrid. Due to high penetration of inverter interfaced distributed generation (IIDG) protection of microgrid is a tedious task. The fault current contributed by IIDGs is limited to 2–3 times the rated current [82]. The fault current varies over a wide range depending upon the type of DG and the power generated by DG.

Different techniques have been employed for detection and classification of faults using techniques based on overcurrent monitoring, sequence components, superimposed components, and transient signals. Traditional fault detection and classification scheme is based on the sequence component of fault current. Figure 14.8 illustrates the basic procedure for detection and classification of faults. It utilizes both current and voltage signals only when current signal data is not adequate to yield correct faulty phase. Otherwise, it operates using current signals only. In the first step, phasor estimation is carried out using three-phase current and

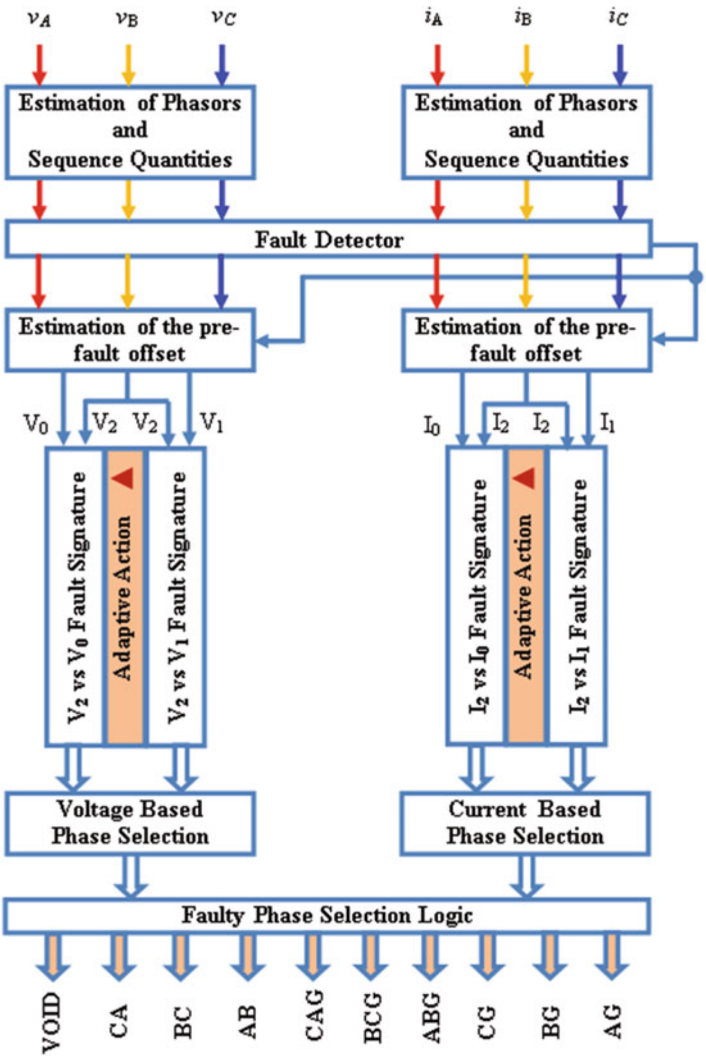


Fig. 14.8 Basic block diagram for classification of faults

voltage signals acquired at the line end and is processed through filter to eliminate DC offset. Eventually, computation of sequence components of fault current is carried out. A proper algorithm for fault detection is executed and the pre-fault DC offset due to loading disturbance are eliminated by deducting pre-fault sequence components from post-fault sequence components.

The conventional protection schemes work effectively for grid-connected mode of operation and are inefficient when DG is disconnected from the utility grid. The scheme employed for protection of microgrid must assure accurate detection and classification of faults during both grid-connected and islanded modes for reliable operation of microgrid.

Adaptive Protection Techniques

Adaptive protection technique is an online system that alters the desired protective response to change in system conditions [83]. In this technique relay settings are automatically readjusted according to the operational mode of microgrid or any alteration in topology of microgrid. Directional overcurrent relays and digital overcurrent relays are employed for such type of protection. The relays are incorporated with a communication system which allows them to interchange the information with respective relays or with central computer to have effective protection.

In [84, 85], centralized adaptive protection of microgrid based on the information stored in the form of event table, fault current table, and action table by microgrid central processing unit (MCPU) is implemented. In event table, all possible microgrid configurations along with status of DGs are stored. Fault current table stores all the information regarding fault current seen by individual relays for all viable fault locations in each configuration. The relay setting for each configuration is stored in action table with order of operation for different faults with definite time lag.

MCPU is updated periodically regarding DG status, configuration of microgrid, and current seen by individual relays at different locations. MCPU issues appropriate signals to the relevant relays with the aid of event table, action table, and fault current table in definite time.

In [86], an adaptive protection scheme without using a communication link between relays is implemented. The technique utilizes voltage signal at PCC for detection of faults. During various overloading events, voltage response is simulated and depending on the magnitude of voltage short-circuit event is distinguished from overloading events. The scheme is only suitable for inverter-dominated microgrids.

For the protection of low-voltage microgrids in both operating modes an adaptive scheme utilizing isolation transformer and energy storage (ES) is proposed in [87]. To determine the operating mode of microgrid overcurrent protection is employed for grid-connected mode and dq0 voltage detection is employed for autonomous mode of operation. To distinguish several protection zones, zero-sequence current is compared with a threshold value.

Adaptive protection techniques are advantageous because they adapt to various configurations and topologies of microgrids. The drawback of implementing aforementioned techniques is the installation of communication equipment which is expensive and complex short-circuit calculations under different operating modes.

Differential Protection

Differential protection scheme is a unit protection scheme which gives protection to an element such as DGs and distribution lines. Differential protection scheme in combination with symmetrical component analysis is proposed in [88] by splitting microgrid into different protection zones to protect the microgrid against single line to ground fault and line-to-line fault. Differential protection is employed for fault detection in upstream zone of protection and, negative- and zero-sequence current components are utilized to detect line-to-line faults in all protection zones and single line-to-ground fault in downstream protection zone. The scheme is capable of detecting faults in autonomous mode also for inverter-interfaced DGs.

A novel differential protection scheme utilizing synchronized phasor measurements and microprocessor relays is discussed in [89]. The scheme is able to identify all types of faults including faults with high fault resistance. A trip signal is issued when the absolute value of two consecutive samples exceeds the pre-specified threshold.

One of the most significant benefits of the implementation of differential protection approaches is that they are reliable for detecting internal faults, not sensitive to bidirectional power flow and reduction of fault current level of islanded microgrids. However, the unbalancing caused due to loading failure in communication system can maloperate the relay.

A differential scheme based on S-transform is implemented in [90]. Three-phase current signals at both ends of distribution line are fetched and processed through S-transform. Difference in spectral energy content of the generated time frequency contour at both ends of line is computed known as differential energy (DE) and is given by the following equation:

$$\mathrm{DE} = E_A - E_B = \{abs\,(S_A\,(j,n))\}^2 - \{abs\,(S_B\,(j,n))\}^2 \tag{14.13}$$

where $S(j, n)$ = generated S-matrix.

j = time samples.

n = frequency steps.

This differential energy is compared with pre-specified threshold for detection of fault. A positive value for threshold is set for fault in grid-connected mode and negative value for fault in islanded mode. The technique is able to detect high-impedance faults in both the operating modes but the technique is nonadaptive and if penetration level of DG is changed threshold setting also needs to be varied for proper detection of faults [91].

To overcome the limitation of aforementioned technique, computation of differential energy is carried out using Hilbert–Huang transform (HHT) [91]. The technique is adaptive in nature as no predetermined set of functions are required and it projects a nonstationary signal onto a time–frequency plane using a mono-component signal [92, 93].

Techniques Employing External Devices

Magnitude of fault current is remarkably distinct between grid-connected and autonomous mode of operation. Hence, designing an appropriate protection system which performs satisfactorily in both the modes of operation is really demanding. In this aspect, there is a scope of deploying a distinct scheme which efficaciously alters the fault current level when microgrid transforms from grid-connected mode to autonomous mode and vice versa, by particular externally placed devices. Fault current level can be increased or decreased with the help of such devices.

To reduce the total contribution of several distributed energy resources during fault, fault current limiters are employed [94] because the fault current level may exceed the design limit of numerous equipment components which may lead to false detection of fault. This contribution is particularly noticeable in case of synchronous machine-based distributed energy resource.

Fault current contribution by inverter-interfaced DGs is limited to 2–3 p.u. To level the fault current level in both grid-connected and autonomous modes of operation, the following approaches are used:

1. Fault current level can be increased to a certain level by installation of energy storage devices, i.e., flywheels and batteries in the microgrid. Thus, conventional overcurrent protection can now be employed for protection [95, 96].
2. By installation of certain devices between the utility and microgrid, to reduce the fault current contribution from main grid [97, 98].

Voltage-Based Protection Technique

Voltage-based techniques are based on identifying voltage disruption at DG end. The output voltage of distributed energy resource is continuously monitored and is transformed from *abc* axis to *dq* axis reference frame. Calculations are simplified as three variables are reduced to two DC quantities. In [99], for detection of fault disturbance signal "V_{DIST}" is extracted by comparing intermittent *d*-*q* values with a reference value. The characteristic of disturbance signal is utilized to detect and classify the fault. The technique is able to protect microgrid against both in-zone and out-of-zone faults by employing communication link between relays located at each DG terminal.

Eventually, in [100] a new fault detection technique based on observing positive-sequence component of the fundamental voltage is implemented so that it is able to maintain the reliability of the system and provides fast fault detection for various types of faults in microgrid. During symmetrical and unsymmetrical fault conditions, the three-phase voltages are transformed into the *d*-*q* reference frame. This transformed voltage magnitude is compared with the amplitude of the fundamental positive-sequence voltages in the d-q coordinate system.

The recent technique in [101] implemented a new protection action based on bus bar fault direction for protection of microgrid in grid-connected as well as islanded modes of operation. Moreover, industrial personal computers (IPCs) have been utilized to design relay protection software and hardware. The drawback in implementation of this technique is that it is unable to identify high-impedance faults and voltage drop within microgrid causes false operation of protection devices.

Conclusion and Future Work

Microgrids are gaining popularity these days due to high requirement of continuous, clean, and cost-effective electricity. Protection requirements for distribution systems incorporated with DGs are quite distinct from those of traditional distribution systems. Rapid and true detection of island is one of the primary issues for protection of microgrid. Several passive and active techniques employed for islanding detection have been illustrated. Passive islanding detection techniques are economical and can be easily implemented. The non-detection zone of active islanding detection techniques is negligible. However, it affects the power quality of the system. The significant features and the potential of islanding detection techniques used have been investigated, to provide effective information for the technique to be used for DG islanding detection.

Coordination among protective devices at PCC, at individual DG, at utility substation should be effectively achieved for efficient protection of microgrid. Traditional overcurrent protection system is influenced by bidirectional power flow. Various techniques for effective coordination settings are discussed in this chapter. Upgrading the protective devices by utilizing adaptive techniques incorporates modification in configuration of microgrid and provides faster protection by employing communication network. However, requirement of extensive memory to store protective settings makes it undesirable for larger configurations.

Reliable operation of microgrid requires accurate fault detection and classification during both grid-connected and autonomous mode of operation. The fault current contribution by inverter-based DGs is too low in islanded mode. Hence detection of fault in islanding mode is difficult. Various techniques employed for high-speed operation have been discussed. Several adaptive techniques employing differential scheme and communication links have been adapted. Differential scheme is preferred for detecting only internal faults. For detection both internal and external fault voltage-based techniques are employed. However, they are ineffective for high-impedance faults and symmetrical faults. Noticeable research gaps and possible future scope in the protection of microgrid have been presented in this chapter.

Future Work

The protection-related study as explained in this book chapter clearly indicates further research directions in the following interesting areas:

1. Breaker information from PCC end can be exploited through a communication channel to identify the islanding condition.
2. Fault-generated high-frequency voltage and current signals in microgrid system during both grid-connected and islanded mode can be exploited for improved and faster algorithms for protection schemes like directional relaying, fault classification, and differential relay.
3. Integrated logics can be applied for better fault detection, classification, and directional estimation.
4. Intelligent electronic devices (IED) can be installed in microgrid system for online directional overcurrent relay coordination.
5. Micro-range PMU can be installed in the microgrid system for better operation, control, and protection.

References

1. Amini, M. H., Boroojeni, K. G., Iyengar, S. S., et al. (2018). *Sustainable interdependent networks: From theory to application*. Cham: Springer.
2. Buldyrev, S. V., et al. (2010). Catastrophic cascade of failures in interdependent networks. *Nature, 464*(7291), 1025–1028.
3. Mohammadi, A., Mehrtash, M., & Kargarian, A. (2018). Diagonal quadratic approximation for decentralized collaborative TSO+DSO optimal power flow. *IEEE Transactions on Smart Grid, 1*, 1. https://doi.org/10.1109/TSG.2018.2796034.
4. Amini, M. H., Boroojeni, K. G., Dragicevic, T., et al. (2017). A comprehensive cloud-based real-time simulation framework for oblivious power routing in clusters of DC microgrids. In *2nd IEEE International Conference on DC Microgrids (ICDCM)*.
5. IEEE Std 1547-2003. (2003). *IEEE standard for interconnecting distributed resources with electric power system*.
6. CIGRE. (1999). *Working Group 37.23 Impact of increasing contribution of dispersed generation on the power system*.
7. Electricity Association Std. (1991). *G59/1 Recommendations for the connection of embedded generating plant to the regional electricity companies distribution systems*.
8. Xu, W., Zhang, G., Li, C., et al. (2007). A power line signaling based technique for anti-islanding protection of distributed generators-part I: Scheme and analysis. *IEEE Transactions on Power Delivery, 22*(3), 1758–1766.

9. Ropp, M. E., Aaker, K., Haigh, J., et al. (2000). Using power line carrier communications to prevent islanding (of PV power systems). *IEEE Photovoltaic Specialists Conference, 2000*, 1675–1678.
10. Ahmad Ku Nurul Edhura, K., Selvaraj, J., & Rahim, N. A. (2013). A review of the islanding detection methods in grid-connected PV inverters. *Renewable and Sustainable Energy Reviews, 21*, 756–766.
11. Report IEA PVPS T5-09. (2002). *Evaluation of islanding detection methods for photovoltaic utility interactive power systems*.
12. Velasco, D., Trujillo, C. L., & Garcera, G. (2010). Review of anti-islanding techniques in distributed generators. *Renewable and Sustainable Energy Reviews, 14*(6), 1608–1614.
13. Timbus, A., Oudalov, A., & Ho, C. (2010). Islanding detection in smart grids. *IEEE Energy Conversion Congress and Exposition (ECCE), 2010*, 3631–3637.
14. Zeineldin, H., El-Saadany, E., & Salama, M. (2006). Impact of DG interface control on islanding detection and non-detection zones. *IEEE Transactions on Power Delivery, 21*(3), 1515–1523.
15. Redfern, M. A., Usta, O., & Fielding, G. (1993). Protection against loss of utility grid supply for a dispersed storage and generation unit. *IEEE Transactions on Power Delivery, 8*(3), 948–954.
16. Nale, R., & Biswal, M. (2017). Comparative assessment of passive islanding detection techniques for microgrid. In *Paper presented at IEEE International Conference on Innovations in Information Embedded and Communication Systems*.
17. Freitas, W., Xu, W., Affonso, C. M., et al. (2005). Comparative analysis between ROCOF and vector surge relays for distributed generation applications. *IEEE Transactions on Power Delivery, 20*(2), 1315–1324.
18. Hu, W., & Sun, Y. (2009). A compound scheme of islanding detection according to inverter. *Asia-Pacific Power and Energy Engineering Conference, 2009*, 1–4.
19. Singam, B., & Hui, L. Y. (2006). Assessing SMS and PJD schemes of anti-islanding with varying quality factor. *Proceedings of the IEEE International Power and Energy Conference, 2006*, 196–201.
20. Mahat, P., Chen, Z., & Bak-jensen, B. (2011). Review on islanding operation of distribution system with distributed generation. *Power and Energy Society General Meeting, 2011*, 1–8.
21. Teoh, W., & Tan, C. (2011). An overview of islanding detection methods in photovoltaic systems. *World Academy of Science Engineering and Technology, 5*(10), 674–682.
22. Kabayashi, H., Takigawa, K., & Hashimato, E. (1991). Method for preventing islanding phenomenon on utility grid with a number of small scale PV systems. *IEEE Photovoltaic Specialists Conference, 1991*, 695–700.
23. Jang, S., & Kim, K. (2004). An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current. *IEEE Transactions on Power Delivery, 19*(2), 745–752.
24. Wang, W., Kliber, J., Zhang, G., et al. (2007). A power line signaling based scheme for anti-islanding protection of distributed generators-part II: Field test results. *IEEE Transactions on Power Delivery, 22*(3), 1767–1772.
25. Pai, F. S., & Huang, S. J. (2001). A detection algorithm for islanding-prevention of dispersed consumer-owned storage and generating units. *IEEE Transactions on Energy Conversion, 16*(4), 346–351.
26. Samui, A., & Samantaray, S. R. (2011). Assessment of ROCPAD relay for islanding detection in distributed generation. *IEEE Transactions on Smart Grid, 2*(2), 391–398.
27. Marchesan, G., Muraro, M. R., Cardoso, G., et al. (2016). Passive method for distributed generation island detection based on oscillation frequency. *IEEE Transactions on Power Delivery, 31*(1), 138–146.
28. Mango, F. D., Liserre, M., & Dell'Aquila, A. (2006). Overview of anti-islanding algorithms for PV systems. Part II: Active methods. *Proceedings of the IEEE 12th International Power Electronics and Motion Control Conference, 2006*, 1884–1889.

29. Ropp, M. E., Begovic, M., & Rohatgi, A. (1999). Analysis and performance assessment of the active frequency drift method of islanding prevention. *IEEE Transactions on Energy Conversion, 14*(3), 810–816.
30. Li, C., Cao, C., Cao, Y., et al. (2014). A review of islanding detection methods for microgrids. *Renewable & Sustainable Energy Reviews, 35*, 211–220.
31. El-Moubarak, M., Hassan, M., & Faza, A. (2015). Performance of three islanding detection methods for grid tied multi inverters. *IEEE 15th Environment and Electrical Engineering Conference, 2015*, 1999–2004.
32. Liu, F., Kang, Y., Zhang, Y., et al. (2010). Improved SMS islanding detection method for grid-connected converters. *IET Renewable Power Generation, 4*(1), 36–42.
33. Lopes, L. A. C., & Sun, H. (2006). Performance assessment of active frequency drifting islanding detection methods. *IEEE Transactions on Energy Conversion, 21*(1), 171–180.
34. Hernandez-Gonzalez, G., & Iravani, R. (2006). Current injection for active islanding detection of electronically-interfaced distributed resources. *IEEE Transactions on Power Delivery, 21*(3), 1698–1705.
35. Karimi, H., Yazdani, A., & Iravani, R. (2008). Negative-sequence current injection for fast islanding detection of a distributed resource unit. *IEEE Transactions on Power Electronics, 23*(1), 298–307.
36. Tuyen, N. D., & Fujita, G. (2011). Negative-sequence current injection of dispersed generation for islanding detection and unbalanced fault ride-through. *International Conference Universities Power Engineering, 2011*, 1–6.
37. O'Kane, P., & Fox, B. (1997). Loss of mains detection for embedded generation by system impedance monitoring. *International Conference on Developments in Power System Protection, 1997*, 95–98.
38. Wrinch, M., Marti, J., & Nagpal, M. (2008). Negative sequence impedance based islanding detection for distributed generation (NSIID). *IEEE Electric Power Conference, Canada, 2008*, 1–6.
39. Pigazo, A., Moreno, V. M., Liserre, M., et al. (2007). Wavelet-based islanding detection algorithm for single phase photovoltaic (PV) distributed generation systems. *IEEE International Symposium on Industrial Electronics, 2007*, 2409–2413.
40. Pigazo, A., Liserre, M., Mastromauro, R. A., et al. (2009). Wavelet-based Islanding detection in grid-connected PV systems. *IEEE Transactions on Industrial Electronics, 56*(11), 4445–4455.
41. Samantaray, S., Pujhari, T., & Subudhi, B. (2009). A new approach to islanding detection in distributed generations. *Third International Conference on Power Systems, 2009*, 25–30.
42. Karegar, H. K., & Sobhani, B. (2012). Wavelet transform method for islanding detection of wind turbines. *Renewable Energy, 38*(1), 94–106.
43. Samui, A., & Samantaray, S. R. (2013). Wavelet singular entropy based islanding detection in distributed generation. *IEEE Transactions on Power Delivery, 28*(1), 411–418.
44. Dash, P. K., Panigrahi, B. K., & Panda, G. (2003). Power quality analysis using S-Transform. *IEEE Transactions on Power Delivery, 18*(2), 406–411.
45. Samantaray, S. R., Samui, A., & Babu, B. C. (2010). S-Transform based Cumulative Sum Detector (CUSUM) for Islanding detection in distributed generations. In: *Joint International Conference on Power Electronics, Drives and Energy Systems (PEDES).*
46. Ray, P. K., Kishor, N., & Mohanty, S. R. (2010). S-transform based islanding detection in grid-connected distributed generation based power system. In *Proceedings IEEE International Energy Conference and Exhibition. (EnergyCon)* (pp. 612–617).
47. Ray, P., Mohanty, S., & Kishor, N. (2011). Disturbance detection in grid connected distribution system using wavelet and S-transform. *Electric Power Systems Research, 81*(3), 805–819.
48. Biswal, B., Dash, P. K., & Panigrahi, B. K. (2009). Non-stationary power signal processing for pattern recognition using HS-transform. *Applied Soft Computing, 9*(1), 107–117.

49. Huang, E., Shen, Z., & Long, S. R. (1998). The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proceedings of the Royal Society of London Series, 1998*, 903–995.
50. Niaki, A. H. M., & Afsharnia, S. (2014). A new passive islanding detection method and its performance evaluation for multi DG systems. *Electric Power Systems Research, 110*, 180–187.
51. Mishra, M., Sahani, M., & Rout, P. K. (2017). An islanding detection algorithm for distributed generation based on Hilbert-Huang transform and extreme learning machine. *Sustainable Energy, Grids and Networks, 9*, 13–26.
52. El-Arroudi, K., Joos, G., Kamwa, I., et al. (2007). Intelligent based approach to islanding detection in distributed generation. *IEEE Transactions on Power Delivery, 22*(2), 828–835.
53. Matic-Cuka, M. K. (2014). Islanding detection for inverter-based distributed generation using support vector machine method. *IEEE Transactions on Smart Grid, 5*(6), 2676–2686.
54. Samantaray, S., Babu, B., & Dash, P. (2011). Probabilistic neural network based islanding detection in distributed generation. *Electric Power Components and Research, 39*, 191–203.
55. Othman, M., & Amari, H. (2008). Online fault detection for power system using wavelet and PNN. *Proceedings of the 2nd IEEE International Conference on Power and Energy, 2008*, 1644–1648.
56. Najy, W., Zeineldin, H., Alaboudy, A. H., et al. (2011). A Bayesian passive islanding detection method for inverter-based distributed generated using ESPRIT. *IEEE Transactions on Power Delivery, 26*(4), 2687–2696.
57. Lin, X., Dong, X., & Lu, Y. (2010). Application of intelligent algorithm in island detection of distributed generation. *Transmission and Distribution Conference and Exposition (IEEE PES), 2010*, 1–7.
58. Sun, R., Wu, Z., & Centeno, V. (2011). Power system islanding detection and identification strategy using topology approach and decision tree. *IEEE Power & Energy Society General Meeting, 2011*, 1–6.
59. Lidula, N. W. A., Perera, N., & Rajapakse, A. D. (2009). Investigation of a fast islanding detection methodology using transient signal. *Proceedings of IEEE Power Energy Society General Meeting, 2009*, 1–6.
60. Samantaray, S. R., Arroudi, K., Joos, G., et al. (2010). A fuzzy rule based approach for islanding detection in distributed generation. *IEEE Transactions on Power Delivery, 25*(3), 1427–1433.
61. Gopalan, S. A., Sreeram, V., & Iu, H. H. (2014). A review of coordination strategies and protection schemes for microgrids. *Renewable Sustainable Energy Reviews, 32*, 222–228.
62. Yang, M. T., & Chang, L. F. (2013). Optimal protection coordination for microgrid under different operating modes. *Mathematical Problems in Engineering, 2013*, 1.
63. Nthontho, M. P., Chowdhury, S. P., Winberg, S., et al. (2012). Protection of domestic solar photovoltaic based microgrid. In *Proceedings of the 11th International Conference on Developments in Power Systems Protection, Birmingham* (p. 1–6).
64. Li, B., Li, Y., Bo, Z., et al. (2009). Design of protection and control scheme for microgrid systems. In *Proceedings of the 44th International Universities Power Engineering Conference (UPEC)* (p. 1–5). Glasgow.
65. Wan, H., Member, K., Li, K., et al. (2010). An adaptive multiagent approach to protection relay coordination with distributed generators in industrial power distribution system. *IEEE Transactions on Industrial Electronics, 46*(5), 2118–2124.
66. Zhu, Y., Shaoqun, S., & Wang, D. (2009). Multiagent-based wide area protection with best-effort adaptive strategy. *Electrical Power and Energy Systems, 31*, 94–99.
67. Laaksonen, H. J. (2010). Protection principles for future microgrids. *IEEE Transactions on Power Electronics, 25*(12), 2910–2919.
68. Sherwali, H. H., & Crossley, P. A. (1996). Expert system for fault location and protection analysis. *IEE Conference Publication, 421*(1996), 181–186.

69. Wayne Hong, H., Chuen-Tsai, S., Mesa, V. M., & Ng, S. (1991). Protective device coordination expert system. *IEEE Transactions on Power Delivery, 26*(1), 359–365.
70. Tuitemwong, T., & Premrudeepreechacharn, S. (2010). Expert system for protection coordination of distribution system with distributed generators. *International Journal of Electrical Power & Energy Systems, 33*(3), 466–471.
71. Girgis, A., & Brahma, S. (2004). Development of adaptive protection scheme for distribution systems with high penetration of distributed generation. *IEEE Transactions on Power Delivery, 19*(1), 56–63.
72. Barker, P. P., & De Mello, R. W. (2000). Determining the impact of distributed generation on power systems: Part 1-radial distribution systems. *IEEE Transactions on Power Delivery, 15*(2), 486–493.
73. Leelaruji, R., & Vanfretti, L. (2012). State-of-the-art in the industrial implementation of protective relay functions, communication mechanism and synchronized phasor capabilities for electric power systems protection. *Renewable and Sustainable Energy Reviews, 16*, 4385–4395.
74. El-Khattam, W., & Sidhu, T. S. (2008). Restoration of directional overcurrent relay coordination in distributed generation systems utilizing fault current limiter. *IEEE Transactions on Power Delivery, 23*(2), 576–585.
75. Ojaghi, M., Sudi, Z., & Faiz, J. (2013). Implementation of full adaptive technique to optimal coordination of overcurrent relays. *IEEE Transactions on Power Delivery, 28*(1), 235–244.
76. Abdelaziz, A. Y., Talaat, H. E. A., Nosseir, A. I., et al. (2002). An adaptive protection scheme for optimal coordination of overcurrent relays. *Electric Power System Research Journal, 61*(1), 1–9.
77. Jo, H. C., Joo, S. K., & Lee, K. (2013). Optimal placements of superconducting fault current limiters (SFCLs) for protection of electric power system with distributed generations (DGs). *EEE Transactions on Superconductivity, 3*(3), 5600–5604.
78. Naiem, A. F., Hegazy, Y. G., Abdelaziz, A. Y., et al. (2012). A classification technique for the assessment of recloser-fuse coordination in distributed generation systems. *IEEE Transactions on Power Delivery, 27*(1), 176–185.
79. Zayandehroodi, H., Mohamed, A., Shareef, H., et al. (2012). A novel neural network and backtracking based protection coordination scheme for distribution system with distributed generation. *International Journal of Electrical Power and Energy Systems, 43*, 868–879.
80. Zeineldin, H. H., Mohamed, Y. A., Khadkikar, V., et al. (2013). A protection coordination index for evaluating distributed generation impacts on protection for meshed distribution systems. *IEEE Transactions on Smart Grid, 3*(2), 1523–1532.
81. Othman, A. M., & Abdelaziz, A. Y. (2016). Enhanced backtracking search algorithm for optimal coordination of directional over-current relays including distributed generation. *Electric Power Components and Systems Journal, 44*(3), 278–290.
82. Keller, J., & Kroposki, B. D. (2010). *Understanding fault characteristics of inverter-based distributed energy resources*. National Renewable Energy Laboratory, Golden, CO, USA, Tech. Rep. NREL/TP-550-46698.
83. Kai-Hui, Z., & Ming-Chao, X. (2011). Impacts of microgrid on protection of distribution networks and protection strategy of microgrid. *Proceedings of International Conference on Advanced Power System Automation and Protection (APAP), 2011*, 356–359.
84. Ustun, T. S., Ozansoy, C., & Ustun, A. (2013). Fault current coefficient and time delay assignment for microgrid protection system with central protection unit. *IEEE Transactions on Power Apparatus and Systems, 28*(2), 598–606.
85. Etemadi, A. H., & Reza, I. (2013). Overcurrent and overload protection of directly voltage controlled distributed resources in a microgrid. *IEEE Transactions on Industrial Electronics, 60*(12), 5629–5638.
86. Tumilty, R. M., Brucoli, M., Burt, G. M., et al. Approaches to network protection for inverter dominated electrical distribution systems. In: Power electronics, machines and drives, 2006. *The 3rd IET international conference on* (p. 622–626). Dublin, Ireland, 4–6 April 2006.

87. Dang, K., He, X., Daqiang, B., & Cunliang, F. (2011). An adaptive protection method for the inverter dominated microgrid. In *Electrical Machines and Systems (ICEMS), 2011 International Conference on.* Beijing, China, 20–23 August 2011. https://doi.org/10.1109/ICEMS.2011.6073457.
88. Nikkhajoei, H., & Lasseter, R. H. (2006). *Microgrid fault protection based on symmetrical and differential current components*. Consortium for Electric Reliability Technology Solutions, contract no. 500-03-024, 2006.
89. Sortomme, E., Venkata, S. S., & Mitra, J. (2010). Microgrid protection using communication assisted digital relays. *IEEE Transactions on Power Delivery, 25*(4), 2789–2796. https://doi.org/10.1109/TPWRD.2009.2035810.
90. Kar, S., & Samantaray, S. R. (2014). Time–frequency transform-based differential scheme for microgrid protection. *IET Generation Transmission and Distribution, 8*(2), 310–320.
91. Gururani, A., Mohanty, S. R., & Mohanta, J. C. (2016). Microgrid protection using Hilbert–Huang transform based-differential scheme. *IET Generation Transmission and Distribution, 10*(15), 3707–3716.
92. Prasai, A., Du, Y., Paquette, A., et al. (2010). Protection of meshed microgrids with communication overlay. *IEEE Energy Conversion Congress and Exposition (ECCE), 2010*, 64–71.
93. Huang, N. E., Wu, Z., & Long, S. R. (2008). Hilbert–Huang transform. In: *Scholarpedia* (p. 2544), Retrieved from http://www.scholarpedia.org/article/Hilbert-Huang_transform.
94. Oudalov, A. (2009). Novel protection systems for microgrids. In *Advanced architectures and control concepts for more microgrids*.
95. Jayawarna, N., & Barnes, M. (2009). Central storage unit response requirement in 'Good Citizen' microgrid. In *Power electronics and applications, 2009. EPE09. 13th European conference on*, Barcelona, 8–10 September 2009.
96. Overbeeke, F. V. (2009). Fault current source to ensure the fault level in inverter dominated networks. In *20th International Conference and Exhibition on Electricity distribution – Part 1, 2009. CIRED 2009*. Prague, Czech Republic, 8–11 June 2009.
97. Kamel, R. M., Chaouachi, A., & Nagasaki, K. (2011). Comparison the performances of three Earthing systems for micro-grid protection during the grid connected mode. *Smart Grid Renew Energy, 2*(3), 206–215 https://doi.org/10.4236/sgre.2011.23024.
98. Khederzadeh, M. (2012). Preservation of overcurrent relays coordination in microgrids by application of static series compensator. In *11th International Conference on Developments in Power Systems Protection, 2012*. DPSP 2012 Birmingham, UK, 23–26 April 2012. https://doi.org/10.1049/cp.2012.0077.
99. Al-Nasseri, H., Redfern, M. A., & Li, F. (2006). A voltage based protection for micro-grids containing power electronic converters. In *IEEE Power Engineering Society General Meeting, Montreal, Que.* 3–5 August 2006. https://doi.org/10.1109/PES.2006.1709423.
100. Hou, C., & Hu, A. (2009). Study of voltage detection based fault judgment method in microgrid with inverter interfaced power source. In *International Conference on Electrical Engineering*. Shenyang, China, 12–15 December 2009.
101. Wang, X., Li, Y., & Yu, Y. Research on the relay protection system for a small laboratory-scale microgrid system. In *Industrial Electronics and Applications (ICIEA), 2011 6th IEEE conference on*. Beijing, China, 21–23 June 2011. https://doi.org/10.1109/ICIEA.2011.5976056.

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