Towards Collaborative Virtual Power Plants

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Abstract. To promote flexible integration of distributed energy resources into the smart grid, the notion of Virtual Power Plants (VPPs) was proposed. VPPs are formed by the integration of heterogeneous systems, organizations and entities which collaborate to ensure optimal generation, distribution, storage, and sale of energy in the energy market. The collaborative nature of VPPs gives the semblance of collaborative business ecosystem, constituted of a mix of highly interdependent relationship among stakeholders. The systematic literature review methodology is used to summarize research evidence of emerging convergence between the Collaborative Networks (CN) and VPP domains. It is observed that, various strategic and dynamic collaborative alliances are formed within a VPP which are similar to various CN organizational forms like: Virtual Breeding Environments (VBE), grasping opportunity driven-networks etc. CN principles like: virtual organization creation, operation and dissolution, negotiation, broker services, etc., are also found. Emerging collaborative forms like hybrid collaborations between known traditional CN forms were also visible.

Keywords: Collaborative Networks · Virtual Power Plants
Distributed energy resources · Energy market · Smart grid

1 Introduction

The VPP concept is rapidly transforming the way we think, design and plan the development of future energy grids. This is because VPPs have the capability of increasing the chances of integrating renewable energy sources into the conventional power grid. The advantage of this development is the enhancement of sustainable energy generation and its subsequent decline in the use of fossil-based energy sources. It also enhances decentralization of the energy grid from a single supply system to a more liberal and diverse supply, based on multiple sources [1]. The VPP concept will also enable small-scale energy producers to participate in the electricity market and will eventually help to overcome the stochastic nature of distributed energy resources (DERs), resulting in a more stable power grid [2].

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The VPP concept is supported by a merge of different technological and managerial concepts, principles and ideas from diverse domains and fields of study. One of such fields is the domain of Collaborative Networks (CN) which embodies knowledge about collaboration amongst heterogenous organizations, systems, and entities which are autonomous in nature and are geographically dispersed. These CNs usually collaborate to achieve common and compatible goals [3].

The objective of this work is to perform a panoramic review of the area of VPPs to primarily identify common grounds where both domains converge. This is necessary because VPPs are constituted of integration of heterogenous systems, organizations, and entities which collaborate to ensure optimal generation, distribution, storage, and sale of renewable energy in the energy market. The main contribution of this paper is the extraction of the underlying collaborative mechanisms, organizational forms, motivation for collaborations, key collaboration agents/players as well as related technologies within the VPP area, using foreknowledge in CNs.

2 Relationship to Resilient Systems

VPPs are anticipated to help in overcoming the stochastic nature of DERs which will result in a more stable and smart power grid. However, with the current level of system integration which includes: high levels of artificial intelligence, smart cyber components, cloud computing, IoT, etc., incorporated in the power grid, coupled with frequent disruptive events around the globe which include: natural disasters, globalization, climate change, economic crisis, demographic shifts, fast technological evolution, terrorism and cyber-attacks, the power grid is becoming more and more susceptible to many forms of attacks which will eventually endanger the sustainability of the grid.

The collaborative and decentralized nature of VPPs however presents a good opportunity to incorporate resilience into the power grid. For instance in [4] a collaborative observation network consisting of multiple DERs within the power system which monitor the behaviors of all its neighbors, and collectively decide to isolate DERs suspected to be under attack is proposed. Again, Egbue et al. [5], concluded in a survey work that micro-grids, which also function collaboratively like VPPs have high potential to increase the reliability and resilience of the smart grid during a blackout or cyber-attack. This is because the decentralized nature of micro-grids/VPPs can provide direct cyber-security benefits if structured properly.

In relation to resilient systems, or towards a resilient power grid, the VPPs concept is hereby perceived as essential components of the grid which cannot simply be overlooked.

3 Survey Approach

To establish a credible correlation of the application of CN principles in the domain of VPPs, the systematic literature review (SLR) method was used. The motivation for this approach is that it provides a balanced and objective summary of research evidence, by evaluating and interpreting available research work, relevant to a particular research question, topic area or phenomenon of interest [6]. SLR is evidence based and has been used extensively by many researchers in other domains.

Systematic Mapping (SM) [7] is a variant of SLR which provides a well-defined structure for any area of research, by categorizing articles in that domain in a way that gives a visual summary or pictorial map of the area. According to [8] the main goals of SM are to provide an overview of a research area and also identify the quantity, type of research and results available within it. A secondary goal can be to identify the forums in which research in the area has been published.

Research Questions. The concept of VPP is found to be relatively new, therefore publications in this area are highly dispersed in terms content and organization. To establish a good synergy and a better synthesis of the area, five guiding research questions are developed to help define the scope of the survey. The research questions are as follow:

Research question 1: What are the key drivers or motivation for collaboration in the domain of VPPs? [Seeking to identify motivation for collaborations]
Research question 2: Which collaborative organizations are emerging in the domain of VPPs? [Seeking to identify organizational forms]
Research question 3: Which collaborative principles are being applied in the emerging collaboration forms? [Seeking to identify CN principles]
Research question 4: Which technological elements support collaboration in VPPs? [Seeking to identify collaborative technological]
Research question 5: Who are the key players, agents or systems that participate in these collaborations? [Seeking to identity key players in the collaborations]

4 Focus Areas

4.1 VPP Aggregation

VPP aggregation is the process of collecting and merging capacities of diverse dispatchable and non-dispatchable DERs, energy storage systems, which may include electric vehicles, controllable loads and demand response programs, etc., to create a composite VPP, which capacity, characteristics and functions are equivalent to a physical power plant. The aggregation method is expected to ultimately impact on the performance and operation of the VPP, hence various approaches proposed by different researchers. Table 1 below summarizes the findings under VPP aggregation with emphasis on motivation for collaboration, collaborative principles that were observed, collaborative forms that were seen, and key players involved in the collaboration.

Table 1. Summary of VPP aggregation

Motivation for collaboration	Collaborative principles	Collaborative forms	Key players/systems
1. Exchange of energy services and information [9] Partner search and selection [9] 2. Facilitate energy trade among DER clusters [10, 11] 3. Shared values such as sustainability, common social cohesion, common geographical location or energy sharing [12] 4. Aggregate energy produced by multiple DER supplier agents and make them available to consumers [13] 5. Build proposals for market bids using meter and sensor information as well as forecast of expected load, production, and flexibility from participating DERs [14] 6. Optimization of profit for Wind Power Producers (WPPs) [15]	1. VO creation processes [9–11, 14] VO operation and dissolution [9–11, 14] VBE broker services [9–12, 14] Partner search and selection process [9–11, 14] VBE administrator services [9–11, 14] Negotiations [9–11, 14] VO alignment with opportunity, operation, and competence [9–11, 14] 2. VPP planer/Market broker [13] 3. Contracts formations [15] Consortium formation [15]	*Traditional CN forms* 1. VBE [9–11] 2. Grasping opportunity driven network [9–11, 14] *Emerging CN forms* 1. Hybrid between VBE and Goal Oriented Networks [9–11, 14]	1. Resource provider [9] DER aggregator [9] DER owners [9] 2. Market operator [10, 11] VDCAs [10, 11] 3. Consumers [12] Small-scale producers [12] 4. DER supplier agents and consumers [13] 5. Aggregator solution [14] Prosumer systems [14] Smart meters [14] Sensor networks [14] Forecasting systems [14] 6. Wind power producers [15]

4.2 VPP Architecture and Infrastructure

VPP architecture and infrastructure covers articles that make contributions to VPP architecture and associated infrastructural support. General software and hardware architecture of power systems and related ICT infrastructure are also considered. In Table 2, a summary of VPP architecture and infrastructure in the context of collaborative technology, collaborative infrastructure, motivation for collaborations and key collaborative players are also analyzed and presented.

Table 2. Summary of VPP architecture and infrastructure

Motivation for collaboration	Collaborative technology	Collaborative architecture	Key players/systems
1. Management of power system through hierarchical architecture that enables integration of high number of DERs [16, 17] 2. To allow direct mapping and implementations in various programming languages 3. Enable effective inter device communication and collaboration	1. System of system technology 2. Multi-agent system technology 3. Artificial neural network algorithms 4. The unified modelling language 5. Communication architecture, technologies and standards such as: IEEE 802.11ac, Long Term Evolution (LTE), IEC 61850, IEC 62746, IEC 61968, IEC 62325	1. Hierarchical, Modular and Scalable architecture [11, 16, 17, 19] 2. Smart-grid Architecture Model framework [20]	1. VPPs at local, regional and district levels [16, 17] 2. Producer agents, consumer agents, and flexible consumer agents [21]

(*continued*)

Table 2. (*continued*)

Motivation for collaboration	Collaborative technology	Collaborative architecture	Key players/systems
4. VPP control and management [18]	standards, TCP-IP based communication protocols, Modbus TCP over Ethernet, Modbus RTU over RS-485	3. Intelligent multi-agent system architecture [21, 22] 4. Hybrid and modular architecture [18] 5. Regionalized multi-agent self-organizing, hierarchical architecture [23]	

4.3 VPP Management

VPP management is the process of organizing and coordinating all resources and activities within the VPP to optimize generation, transmission, and distribution of energy. VPP management results in cost and loss minimization and ultimately maximizes profit. In this work, the authors considered publications that made contributions to various aspects of VPP management. In this focus area, VPP managerial techniques as well as collaborative principles were analyzed. Additionally, motivation for collaborations and key collaborative players/systems were also reviewed. Table 3 present the findings under this focus area.

Table 3. Summary of VPP management

Motivation for collaboration	VPP management technique	Collaborative principles	Key players/systems
1. Resource sharing [24] 2. Address supply and demand mismatches in the grid [25] 3. Minimization of electricity bill for micro-VPP participant [26]	1. Contractual agreement for resource sharing [24] 2. Smart Energy Aggregation Network (SEAN) [25] 3. A business model in the form of services [26] 4. Formation of dynamic groups to handle optimal dispatch of local resources [18] 5. Adoptation of social concept of trust to measure the quality of predictions in the market [23] 6. Sustainable energy micro-system inside a residential building [27] 7. Management through dynamic price mechanism [28] 8. A multi-agent system approach to energy resource management [22]	1. Principle of resource sharing as used in collaborative virtual laboratory is visible, Partner search and selection processes, Internal consortium formation, call for tenders [23, 24] 2. Principle of trust [23] 3. VBE formation [23, 28] 4. VO administrator and broker, VO creation and broker services, VO planner, VO manager and VO coordinator is also visible [22]	1. Network operator, DER owners, Controllable loads, storage systems [25] 2. Residential community of multiple apartments [26, 27]

4.4 VPP Market

The core objective of VPPs is to enable DERs participation in the energy market. The energy market is a trading system that enables purchases, through bids for buying or selling, or through offers and short-term trades, generally in the form of financial or obligation swaps. Bids and offers use supply and demand principles to set the prices. In this work, the authors considered publications that covered tariffs, remunerations and negotiations within the VPP market. The focus here was to identify collaborative technology and collaborative principles within the VPP market.

Table 4. Summary of VPP market

Motivation for collaboration	Collaborating technology	Collaborative principles	Key players/systems
1. Introduction of new market players to modify current energy ecosystem [2] 2. Simulation of a multi-level negotiation mechanism for VPP in the energy market [29] 3. Autonomous VPPs that can decide whether to aggregate into a VPP or negotiate energy prices alone and outside the VPP [30] 4. VPPs to offer optimum remuneration packages to both customers and producers in the cluster [31] 5. clustering approach for a fairer tariff group organization that considers the resource type and the importance of each participating resource in each specific scenario [32] 6. Strategic bidding for VPPs [33] 7. Remuneration and tariffs [34] 8. Intelligent VPP remuneration [35]	1. Electronic notary [36] 2. Coalition formation theory [29] 3. Agent based-modelling and simulation [29, 30, 36] 4. Dynamic strategies [2] 5. Game theory for scenario analysis 6. Resilient systems, [30] 7. Cluster formation and dynamic system [2, 31, 32]	1. VBEs and dynamic VO creation using dynamic aggregations processes [2] 2. Application of e-Notary concepts [36] VO administrator services [36] 3. Grasping-opportunity driven networks [36]	1. VIMSIN Prosumers (individual prosumers) [2] VIMSIN Micro-Grid Aggregators [2] Virtual Micro-grid [2] Telecom Provider [2] 2. Market operator agent, System operator agent, Market facilitator agent, Buyer agents, Seller agents, VPP agents, VPP facilitator agents [36] 3. Clusters of producers and consumers [31] 4. Distributed generation units, DR programs, and suppliers [32]

4.5 VPP Security

VPP networks are supported extensively by ICT infrastructure which are deployed to enable wide area monitoring, protection, and control of the grid. With this kind of integration, the traditional power system is gradually evolving into a cyber-physical entity that is constituted of distributed smart devices which will eventually subject the power grid to cyber related attacks. VPP security therefore a very critical components future grid. Under this section (Table 5), the authors considered collaborative technologies, motivation for collaboration and key collaborative players under VPP security.

Table 5. Summary of VPP security

Motivation for collaborations	Collaborative technology	Key players/systems
1. Multi-layered security approach that can repel attacks and also help better contain cyber intrusions [37] 2. Prompt detection of cyber related attacks [38] 3. To enhance cross-layered grid security against pervasive and persistent attacks [38] 4. Simulate a security system that supports scalability and also insure system security in the distribution network [39] 5. Deploy a security system to detect intruders who may impair proper operation of the grid [40] 6. Simulate an attack-resilient cooperative control strategy [4] 7. Proposes a holistic attack resilient framework to protect the integrated DER and the critical power grid infrastructure from malicious cyber-attacks [41] 8. Assist in circumnavigation of software defined network (SDN) substations that may come under attacks [42] 9. To incorporate the concept of "mutual suspicion" which enables peers to protect themselves and their neighbours in the network [5]	1. Integration of security in cyber physical systems [5, 37, 38, 40, 41] 2. Multi-agent approach to system security 3. Hierarchical systems [39] 4. Software defined network technology [42] 5. Machine leaning techniques for deploying system security [5, 37, 38, 40, 41] 6. Artificial intelligence for system monitoring and intrusion detection [5, 37, 38, 40, 41] 7. System of system technology for integrating security at various levels of smart-grid architecture [37–39]	1. Cyber-security layer Behaviour estimation layer, and a physical security layer [38] 2. Control Centre Cloud, Primary Substation Cloud, Secondary Substation Backbone Cloud, Secondary Substation Cloud [39] 3. Low Level Intruder Detection System (IDS), Medium Level IDS and High Level IDS [40] 4. Cyber-threat modelling framework, resilience analysis framework, attack prevention and detection framework, and collaborative response framework at the cyber, physical, and utility layers of the power system [41] 5. SDN substation, SDN gateway switch, global SDN controller [42]

4.6 VPP Policy and Roadmaps

Under this section, the authors considered short-term and long-term policy documents that support plans intended to guide the development of technologies that will enhance communication and collaborative technologies in the smart grid (SG).

Table 6. Summary of VPP policy and roadmaps

Motivation for collaboration	Collaborative technology/roadmaps	Key players/systems
1. Develop a set of baseline requirements for information security within the SG [43] 2. Proposed the need to agree on a minimum level of security requirements for all components and systems that interconnect to support SG communications [43] 3. Proposition of a sub-roadmap for DR programme using the city of Oregon and the Pacific Northwest as case study [44] 4. Introduction of disclosure policy about cyber vulnerabilities [45] 5. Adaptation of utilities towards various enterprise ICT-architectures to ensure systems reliability and optimize new business capabilities [46] 6. Incorporate policy actions to promote utility access to spectrum by enabling utilities to share public safety spectrum and also share federal spectrum [47] 7. Implementation a green-growth plan as a national policy task [47]	1. Technological roadmaps for DR programs [44] 2. Roadmap to address various cyber security and associated vulnerabilities concerns [45] 3. Roadmaps for the advancement of ICT architectures and infrastructure to enhance smart grid enterprises and different business models [46] 4. Wireless communication technologies through spectrum allocations and sharing [47] 5. Smart grid prototyping [47] 6. Fully functional smart grid society [47]	1. The energy supply value chain which comprises: generation, transmission, distribution and load [43] 2. Various smart appliances running demand response program in the smart grid [44] 3. All entities connected to the grid [45] 4. Utility companies, Federal agencies [47] 5. Smart grid society in Korea [47]

5 Conclusions

The following general remarks can be made based on the outcome of the survey

(a) Various CN organizational forms, principles, concepts and technology have significant level of penetration within the VPP concept.

(b) VPPs are found to form various strategic and dynamic collaborative alliances which are similar to various CN organizational forms.
(c) Prospects for new and hybrid collaborative forms and mechanisms are very high within VPP energy ecosystem.
(d) The two communities were found to use different languages or terminologies although referring to similar concepts. For instance, in the VPP domain, the process of accumulating DERs is called "aggregation". However, a similar process in the domain of CNs is referred to as a "VO creation". Another process in CNs called "partner search and selection process" occurs in the VPP domain, however, this process is named differently and adopts different functional approach. Some examples include the Common Active Registry [9] and Virtual DER Clustering Aggregator [10, 11]. This suggests the need for the two communities to engage in further interactions to develop inter-disciplinary knowledge-base.
(e) The discipline of CN constitutes a matured, well defined and clearly structured body of knowledge in various aspects of collaborations across diverse disciplines. By adopting CN body of knowledge within the VPP collaborative environment, the VPP concept and its associated technologies can greatly be enhanced. A merge between these two disciplines could forge a clear niche for a collaborative VPP ecosystem which is agile and highly resilient.

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