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Recent advances on smart grid technology and renewable energy integration

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With the integration of renewable energy generations and other related changes, the smart grid, or the future electric power system, is confronted with new challenges and opportunities. Therefore, it is a promising subject in electrical engineering and much work has been done on it. This paper reviews the recent advances on the technologies of smart grid and renewable energy integration, from the aspects of modeling, simulation, protection and control, stability, operation, and planning.

smart grid, renewable energy integration, modeling, simulation, protection and control, stability, operation, planning

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Fossile energy crisis and pollution are two major challenges to modern electric industry. The gravity of the situation has triggered the worldwide academic discussions and engineering practices of the next-generation of power grid. It is widely accepted that the smart grid is a feasible and powerful choice to meet future challenges [1].

Compared with traditional power grid, the smart grid has the following salient features: high proportion of renewable energy generation on the source sides, smart and robust operations and control strategies on the electric networks, and diversification of demands on the load sides.

Large-scale renewable energy integration has injected vitality into the research and application of the smart grid [2]. The non-deterministic and low dispatchable characteristics of renewable energies force system operators to draw up more flexible and robust operating decisions. To some extent, eco-friendly and distributed characteristics of renewable energies may meet the demands of diverse loads. And surely, renewable energy integration has expanded the components of power sources, therefore, the development technologies of smart grid and renewable energy integration are strongly connected, and the breakthrough of one would promote the improvement of the other.

In the last few years, a great number of valuable results on various aspects of smart gird technology and renewable energy integration have been achieved, such as system modeling, simulation, protection and control, stability, transient stability, operation and planning [3].

As a result, this paper reviews the typical research focuses on smart grid technology and renewable energy integration, based on an extensive and comprehensive survey over the most authoritative journals in electrical engineering, such as IEEE Transactions on Power Systems, IEEE Transactions on Sustainable Energy, IEEE Transactions on Smart Grid, Science China Technological Sciences, etc. Original ideas, innovative mathematical formulations, effective solution methodologies, and prospective engineering practices are introduced and discussed in this review.

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1 Modeling

System modeling is one of the most fundamental problems of smart grid and renewable energy integration. In this section, modeling advances at system level, equipment level, and resource level are reviewed respectively.

1.1 System level

The power system consists of many subsystems such as generation system, transmission system, substation system, and consumption system. Many researchers have done interesting modeling work at the system level.

Generally speaking, electromagnetic transient simulation on large-scale power system is time-consuming. A new frequency-dependent equivalence method was proposed in ref. [4]. A high-efficient algorithm was developed to transfer the port admittance determinant of mixing matrix into admittance rational function directly. Numerical results showed that the computation time varied nearly linearly with the scale of the test system. A matrix method was provided in ref. [5] to analyze the life cycle inventory of the power system. This method focuses on power-generating ability and environmental performances of the power system. Results indicated that the method needs less time to analyze the system compared with traditional methods. State estimation is the foundation and core of modern energy management systems. Traditionally, the reliability of parameter estimation is usually neglected and the measurement redundancy is not fully considered. Therefore, accuracy and reliability of the estimation were improved in ref. [6] by a proposed assessment framework for branch parameter estimation. Computational experiments showed the correctness and effectiveness of the proposed assessment framework.

At the subsystem level, the existing load equivalent methods usually neglect the dynamic features of loads such as induction motors, and deal with static load models only. A new dynamic equivalent method considering motor dynamics was presented in ref. [7]. The dynamic equivalent method perfectly held the original dynamic performance of induction motors and the test results proved its efficiency. Analysis of power transmission loss is a hot topic in the field of system operation. A calculation model of power transmission loss for cable-in-conduit conductor (CICC) based on strain was discussed in ref. [8]. Results showed that by adopting this method, the calculation relative error was less than 40%. A wind farm model using probabilistic clustering was proposed in ref. [9]. Numerical tests showed better dynamic responses than the full wind farm model.

1.2 Equipment level

Modeling at the equipment level is essential, when we focus on the problems of local parts of power system, such as angle stability, local control, and efficiency analysis.

Hydraulic power has the highest proportion of energy consuming among all kinds of renewable energy. However, there is still around 20% energy loss in the hydro turbines. A comprehensive analysis of composition of energy loss occurring in the hydro turbine was presented in ref. [10]. Simulation results matched perfectly with measurements and indicated that the presented model could represent the inner energy loss features of the hydro turbine. Inner energy loss is also the bottleneck of the efficiency of thermal turbine. A model of metal hot-electron power generation based on hot electron emission theory was built in ref. [11] and it was helpful to enhance efficiency of thermal turbine. The experiments showed the effectiveness of the proposed model. In the actual power system, transmission line shows different features under different levels of currents. An optimized transmission line model under lighting currents was presented in ref. [12]. Then a detailed discussion on the effective lengths of horizontal grounding electrode was provided. The modeling of wind turbines are key points to the accommodation of wind power. An approximate wind turbine control system model for wind farm power control was presented in ref. [13]. The results suggested that the proposed model could be applied to real wind farm control. A wind turbine power curve can show the dynamic performance of the related wind turbine. An advanced algorithm for wind turbine power curve modeling was presented in ref. [14]. The computational results indicated the algorithm was much more efficient than other existing algorithms.

1.3 Resource level

In modeling and analyzing electric equipment, energy resources are treated as input variables. However, the detailed modeling of resources are needed when we deal with problems related to resource assessment.

Studies on numerical site calibration over complex terrain for wind turbines were presented in ref. [15]. The results showed better generating performance by using the wind speed on the meteorological mast. A novel prediction methodology composed of chaotic operators to predict the wind speed series was presented in ref. [16]. The proposed methodology was based on Kalman filter. Experiments showed great improvement of wind speed prediction and proved the effectiveness of the methodology. An extensive investigation on the spatiotemporal complementarity of wind energy resources in China was provided in ref. [17]. An assessment model for a hybrid energy conversion system with wind and solar resources was presented in ref. [18]. The proposed model could be applied to many aspects such as assessment of resource benefits including capacity factors and reserve requirements.

2 Simulation

Complexity is a typical characteristic of large-scale modern power system, which increases the challenges to simulation instruments. Even the latest simulator, RTDS, has some drawbacks, and cannot perfectly meet all the needs in power system. Therefore, new simulation algorithms need to be put forward. At the same time, simulation tools also need to be renewed. In this part, some novel simulation algorithms are introduced and some tools are depicted, which may enhance the ability of time-domain dynamic simulation on modern power system.

2.1 New algorithms

With the fast development of power system, the system topology is getting more complex and the numbers of components increases fast. These bring in difficulties in analysis and simulation of the smart grid. Fast and real-time simulation can be hardly achieved by conventional simulation algorithm, therefore there is urgent need in new and advanced simulation algorithms. In this part, some new algorithms are presented to deal with electro-magnetic transient program (EMTP) in power system.

To solve the linear equations arising in the time-domain simulation, new type of preconditioners was proposed in iterations [19]. The results showed that the multifrontal preconditioned iterative methods could improve computational efficiency. In ref. [20], a time-domain transformation was proposed, which accelerated the EMTP in dynamics and made EMTP more convenient to implement. Time-domain simulation is also important in power system stability. When updating preconditioner strategy is used, the iteration decreases dramatically [21]. In ref. [22], tradition Jacobian matrixes was abandoned and Newton-GMRES(m) method was proposed to solve dynamic power system simulation, which had strong parallelizability and enhanced efficiency. Component level parallelization and the multi-area thevenin equivalent (MATE) method was proposed in ref. [23], and a higher efficiency was achieved. The shifted-frequency-analysis theory was proposed in ref. [24], which made it easier to get time-domain simulation results. In summary, time-domain simulation is very important in modern power system, and many methods have been proposed.

In ref. [25], the aging trend of component was considered in power system reliability evaluation, and a new aging model was built, which was significant in reliability computation especially in planning.

2.2 Novel tools

Since some new simulation algorithms have been proposed, certain tools are needed. Therefore, tools for power system simulation are also important, which determine the accuracy and efficiency of simulation algorithms.

To solve power system dynamic simulation effectively, some new tools are studied. In ref. [26], a fast cycle-accurate instruction set simulator (CA-ISS) was developed, which makes simulation faster than convention tools. The CA-ISS also has good performance even using a personal computer. The phasor tool for real-time transient stability simulation introduced in ref. [27] can improve the contingency studies in large-scale power systems. The accuracy is better compared with other non-real-time transient stability simulation tools. In ref. [28], a Matlab-based toolbox was exploited, which allows user to define model independently. The toolbox has a wide range of integration routines and is easy to use, which makes it a bright future. Sometimes, result is not very accurate and convincing using only one simulation tool, therefore, co-simulation was developed. In ref. [29], a framework for co-simulation with more than one tool was present, and the result was better than that using only one.

There are many other simulation tools in power system simulation as introduced in ref. [30]. Simulation results are related with simulator closely, so more attention should be paid to simulation tools.

3 Protection and control

Modern power system is becoming much more complex and nonlinear, thus it calls for sophisticated protection and control strategies to guarantee that the system works well.

The power system has two trends of development: large scale power system and distributed generation systems, such as microgrids. Since they have different features, different protection and control techniques are needed, respectively.

3.1 WAMS and advanced PSS

Few advanced devices are used in traditional power system to monitor the operation state, which has little information for protection and control. However, in a modern large scale power system, with the help of wide area monitoring system (WAMS), it is possible to acquire much more important information to improve the protection and control abilities.

A novel wide-area nonlinear excitation control strategy for multi-machine power systems was presented in ref. [31]. The proposed method not only considers time delays of remote signals, but also avoids the impact of wide-area information's incompleteness since not all generators are installed with phase measurement unit (PMU).

In ref. [32], a stability assessment solution based on phasor measurement data was described, which gave insight into experiences gained from actual WAMS. The paper also concluded that WAMS allowed the stepwise upgrading from monitoring to protection and control functionality.

Ref. [33] proposed new technologies for communication in power system to create new opportunities for developing wide area system monitoring, protection and control, called virtual protection system (VPS). The VPS is a system that can be realized in control center to detect any system abnormalities in a virtual environment. Through using PMUs data from the whole system area, the control system can use the VPS to detect system states and apply it to self-healing of power systems.

With the widely use of WAMS, it is helpful to design advanced PSS, which can solve the low frequency oscillation problem and improve the stabilities.

In ref. [34], it was proved that the classical PSS design principles based on synchronous torque as well as the damping torque were not theoretically sound. Then the paper discussed the linear optimal controller design method and analyzed its relations with the conventional PID design. The paper revealed the real mechanism of the PSS and proposed to use more systematic and advanced monitoring system to enhance the performance of PSS.

Another advanced PSS, called global power system stabilizer (GPSS) based on WAMS, was presented in ref. [35]. It aimed to damp inter-area modes and to protect the whole power systems.

3.2 Power electronics interfaced devices(PEIDs)

The distributed generations (DGs) are normally controlled and connected to the grid through PEIDs, such as converters, PWM rectifiers and MMC, therefore proper protection and control strategies are needed.

Reliable operation of a DGs-based microgrid requires advanced power flow control and local voltage control. Moreover, system protection mostly should coordinate with each DG to ensure reliable operation.

In order to improve the performance of PEIDs, many control strategies have been proposed. Ref. [36] put forward a direct power control for three-level PWM rectifier based on hysteresis strategy, which could balance the neutral-point voltage, realize the unity power factor operation and stabilize the DC bus voltage.

DC faults ride-through capability of full-fridge modular multilevel converter (MMC) was analyzed in ref. [37]. In this work, the protection performance of MMC was significantly improved.

As many PEIDs have been integrated with microgrids, its protection and control are not only about the devices but also related to the system. In ref. [38], considering customer comfort feeling and combining family-friendly controllable refrigerators, a novel decentralized demand control strategy was proposed to regulate the frequency of microgrid working with the energy storage system. Some new control methods were presented for the sake of seamless transfer between two modes of microgrid [39–42]. For example, ref. [39] proposed a control strategy based on master-slave control, which could achieve smooth transition between stand-alone operation mode and grid-connected operation mode. Furthermore, a seamless control method considering response time of different mode transitions under abnormal conditions such as grid faults was presented in ref. [42].

Moreover, some vital techniques were posed to protect and control the PEIDs or microgrid [43, 44]. The protection and control scheme for microgrid systems was designed in ref. [43]. And ref. [44] discussed control and protection of power electronics interfaced distributed generation systems in a customer-driven microgrid. They all provide some useful thoughts to solve the problems in the field of protection and control.

4 Stability

Stability analysis is a traditional but important aspect in power system. As the technologies of the smart grid and renewable energy develops fast, new problems come up on the subjects of small signal stability, transient stability, voltage stability, secure assessment, etc.

4.1 Small signal stability

Small signal stability is of great importance to power system stability. With the methods and tools in small signal analysis, people can find something about the damping characters of the system.

In order to provide more flexibility and reliability, new voltage source converters (VSCs) are injected to grid, such as STATCOM (static synchronous compensator), fuel cell, photovoltaic generation, etc. In ref. [45], the effects of those VSCs on power system damping oscillation were investigated. The main conclusion drawn from the research was that both dynamics and DC voltage control can provide either positive or negative damping torque depending on the load level. Hence, a point existed at which the added damping torque was zero. In other words, VSCs had no impact on power system damping oscillation.

The classical method to analyze the randomness' effects on power system stability is using deterministic differential theory. However, when considering outside excitations, which might be caused by renewable energy source, the traditional theory doesn't act well. The stochastic differential equation in ref. [46] was introduced to solve this problem. By Euler-Maruyama numerical method, the author proved that small Gauss type random excitation would not produce new stability problem.

With PMU/WAMS gradually set in smart grid, some problems were well solved. In ref. [47], a revised stochastic subspace method, based on measurement, was proposed to estimate the electromechanical characteristics of low frequency oscillation. This method could obtain the mode shapes and mode together in less computation without sacrificing accuracy. The on-line application was approaching.

As for microgrids and wind-farms, new researches have been reported. Sensitivity of eigen-solutions is critical to microgrid studies for its great contribution to control variables, etc. The matrix perturbation theory introduced in ref. [48] was an efficient computing method for variations response characteristic in microgrids. In ref. [49], an 'analytical' method to investigate the stochastic uncertainties of wind farms for power grid small signal analysis was proposed. This work showed that high penetration of wind power would bring risk to a stable power system operation.

4.2 Transient stability

Estimation of a nonlinear system's transient stability region is critical, thus it always attracts much attention. New theories and methods have appeared in recent years.

Fast and easy calculation of unstable equilibrium point (UEP) with accurate load models is an interesting object. Considering induction motor's high proportion in power system and great effects of transient stability, a novel method continuation-based was proposed in ref. [50] which could obtain multiple UEPs when tracing the T-s curve from the stable equilibrium point.

In ref. [51], a numerical algorithm, based on a quadratic form local input-to-state stability (LISS)-Lyapunov function, was presented for estimation of LISS properties. Given linear matrix inequality's development, this algorithm was easily implemented and powerful. In ref. [52], the flow map was used for the expansion of estimated stability region. And the enlargement or compression could be directly obtained from the diffeomorphism.

Photovoltaic (PV) system's impact on transient stability in transmission network was proposed in ref. [53]. This work examined that PV system could reduce inertial of power system on transient stability. Simulation also verified both beneficial and detrimental impacts of PV system. The relationship between wind generation and the rotor angle stability of conventional synchronous machine was explored in ref. [54]. Proper control strategies of a wind farm's voltage and reactive power could minimize angular separation, or even provide extra support for synchronous machines.

4.3 Voltage stability

High penetration of renewable energy requires much reactive power, which may lead to voltage instability. Nowadays, voltage stability may be one of the most threatening factors in promoting wind penetration level.

The unpredictable wind speed and random power fluctuation of wind farms result in high risk for power system. On-line security monitoring is of great need. In ref. [55], an approach was developed to determine the local boundaries of voltage stability region with uncertainty from wind farms. Parallel calculation was also implemented to improve the efficiency.

Finding voltage stability margin (VSM) on-line is a hot topic. In ref. [56], statistical multi-linear regression models were utilized to investigate the relationship between reactive power reserves (RPR) and VSM. Hence, the VSM played as an indicator to estimate VSM in online environment. A method in ref. [57] provided a comprehensive solution to identify system weakness at different wind penetration levels, and increased the voltage stability of power gird by placing SVCs at weakest buses instead of wind generation buses.

4.4 Security assessment

With complexity of the inter-connection of growing power grids and uncertainties from high penetration of renewable energies, traditional security assessment cannot meet requirements in new circumstance. Obviously, a scientific and effective assessment will help operators take proper preventive control.

To deal with new random factors, such as wind power and load demands, probabilistic steady-state and dynamic security assessment models were set up in ref. [58]. Time to insecurity, here as a security index, could be obtained and helpful for preventive operation.

As power grid changes its form, subsynchronous oscillation (SSO) with low amplitude may occur more frequently. Research work in ref. [59] indicated that time-domains simulation could be used to assess different equipment' effects and FACTS had a stronger ability to mitigate SSO by supplying more damping torque.

High integration of wind power makes security assessment with stochastic variable in great need. A probabilistic framework for designing an 'N-1' secure day-ahead dispatch was achieved for power systems with wind power [60].

5 Operation

Large scale integration of renewable energy imposes great challenges on many aspects of smart grid operation. The challenges are due to the uncertainty characteristics of renewable generations. Mach work has been focusing on this issue in recent years.

5.1 Unit commitment

Many innovative methods of day-ahead unit commitment have been proposed in recent years to ensure the power systems' capability to balance load in real-time operation. An adaptive robust security-constrained unit commitment model considering wind power uncertainty was proposed in ref. [61]. The solution could be immune to any realization of wind power generation in given uncertainty set and a practical methodology combing Benders decomposition and outer approximation method were developed to solve this problem. Considering other energy storage devices in robust dispatch, a robust unit commitment model in a wind-thermal-pumped hydro storage power system was proposed in ref. [62] with the objective to minimize the maximum cost increment caused by wind power fluctuations. As the worst case was considered previously and pumped hydro storage was included, the risk and cost of power system operation were effectively decreased. With more flexibilities incorporated, demand response and wind power in a two-stage unit commitment model to both hedge wind power uncertainty and reduce operation cost was integrated in ref. [63]. The robust optimization method to security-constrained unit commitment to guarantee the reliability of power system operation in case of N-k contingency was extended in ref. [64].

Unit commitment also comprises scheduling of wind farms. An optimal short-term dispatch strategy of a single wind farm was presented in ref. [65], where a fuzzy clustering algorithm was developed to divide different wind groups after obtaining the characteristic vectors of wind units and characteristic matrix of the wind farm.

5.2 Economic dispatch

5.2.1 Active power regulation

Balancing system loads while accounting intermittency of renewables in real-time operation is another huge challenge. An affinely adjustable robust OPF (AAROPF) to accommodate the uncertainty of renewables was proposed in ref. [66]. The non-adjustable base-point thermal generation was determined before realization of renewables and the generation changes according to the realizations of renewable generation linearly. The results showed a modest cost increment with uncertainty in reasonable levels and better performance compared to methodology via uncertainty scenarios. To incorporate the flexibilities of adjustable load, a new strategy to tracing renewables' fluctuations via demand response while satisfying the customers' comfortableness was proposed in ref. [67]. Fast spinning reserve could also be provided through this method in contingency.

Distributed optimization with nonlinear constrains in distributed power networks are more complicated than the current central optimization problem with linear constrains. New methodologies such as game theory or convex optimization may be used to analytically handle this problem incorporating renewable resources [68].

In the research of smart grid operation, a new method of reserve scheduling was presented in ref. [69] as reserve determined by existing methods may be unreachable. The optimization dispatching was then modeled as a continuous-time optimal control problem. The computation burden to solve this problem was greatly reduced by reformulating it to a nonlinear programming problem.

5.2.2 Voltage regulation

The voltage regulation is an important technique to guarantee the power quality of a smart grid. However, traditional regional-based control methodology may impose un-neglected impacts onto its adjacent areas. A multi-level multi-area hybrid automatic voltage control (MLMA-HAVC) system that could effectively solve this problem through the coordination of different control areas was proposed in ref. [70]. Application of MLMA-HAVC in Northeast China Grid validated the effectiveness of this method.

When accounting renewables, significant voltage rise in the feeder may be incurred by active power injection from photovoltaic (PV) generation. Thus, frequent operation of tap changers or voltage regulators may be resulted in. To hedge this problem, a strategy to minimize the mechanical operation of controllable devices while satisfying typical security constrains and incorporating the voltage support capability of PV generation was proposed in ref. [71].

5.3 Topology optimization

Distributed feeder configuration (DFR) is a practical way to reduce power loss in operation. However, the DFR problem is of highly complexity and is hard to solve. An innovative method combing self-adaptive particle swarm optimization (SAPSO) and frog-leaping algorithm (SFLA) was presented in ref. [72], which had stable solutions and effectively improved the computation performance. The dual formulation of OPF problem had a natural decomposition of system load and the topology of power networks was investigated in ref. [73], which could be used to search DFR solutions with a higher efficiency.

6 Planning

Planning is the first and indispensable stage in the life span of a practical electric power project, and it attracts more attention in scientific research. What' s more, with the development of related technologies mentioned in the above sections, the planning of smart grids is confronted with new opportunities and challenges.

6.1 Transmission network expansion planning

Transmission network expansion planning (TNEP) is a relatively complex problem under the subject of electric power system planning. It is usually an optimization problem that aims at finding an economic planning scheme to meet the demands during a certain planning period [74,75]. It is said to be a nonlinear and non-convex problem [76], which is hard to solve directly, thus approximations are traditionally used. For instance, conic programming relaxation was applied in ref. [75] to deal with a TNEP problem with an AC network model considering power flow and voltage limits.

Having a convex relaxation, this mixed-integer optimization problem could be solved by a branch-and-cut algorithm. Though approximation was used, it was still more valid than general DC network planning models. Besides approximation of a model which makes it easier to solve, there are also other methods. A new idea was put forward in ref. [76], where a discrepancy-bounded local search (DBLS) method was presented, using a black box to cover and model complexity of power flow. And the algorithm should be decoupled with the specific power flow model. Both DC power flow model and AC power flow model were studied, and results showed that they did affect the costs.

Many uncertainties have been brought to electric power systems since integration of renewable energy generations. Therefore, we need new or improved models and methods to solve the related planning problems. Robust transmission network expansion planning (RTNEP) is one of them, and a general static TNEP model is a mixed integer nonlinear optimization problem. Usually, renewable generations and loads are considered as uncertainties, such as in refs. [74] and [77], which are described by simple uncertainty sets and do not need information of related probability distributions. Taguchi's orthogonal array testing (TOAT) method, which is a traditional approach in robust optimization and is very popular in the field of quality engineering (QE), was used in ref. [74] to select testing scenarios in the RTNEP problem. In ref. [77], with the use of Benders decomposition (BD), the model turned to iterate between a master problem and a slave problem. What's more, both problems could be solved by existing optimization software, since they were mixed-integer linear programs. Nevertheless, RTNEP is not the only method. Modifications on previous modeling and approaches can also adapt the uncertainties brought by renewable energies. For example, the authors in ref. [78] employed an improved Monte Carlo simulation method to evaluate flexibility of the studied system, which was related to uncertainties, and flexibility was one of the objectives in the presented multi-objective optimization model for TNEP. In ref. [79], more attention was paid to the assessment of security, in which the costs of preventive control, emergency control and social losses were related to the uncertainties of load and wind power. In such a case, both steady and dynamic aspects were considered in the TNEP optimization model.

6.2 Distribution network expansion planning

Distribution network expansion planning (DNEP) aims at finding or determining the minimum cost for expansion plan, which guarantees enough capacities of substations and lines for forecasted load demands during the planning horizon [80]. It was found that a general DENP optimization problem could be modeled as a disjunctive conic program precisely with equivalent formulations in ref. [80]. What's more, with the help of tight polyhedral approximations, these two formulations could be solved by specific software dealing with mixed-integer linear programming (MILP). Multistage DNEP can be considered as a special or an advanced DNEP problem, which also attracts researchers' attention, and various novel or modified algorithms can be employed. A novel balanced genetic algorithm (BGA), which is a modified genetic algorithm (GA) was used to ensure diversity of strategies, and a modified data envelopment analysis method (MDEA) was adopted to guarantee flexible and objective comparisons in ref. [81] to solve a multistage DNEP problem. Unit commitment (UC) scheduling was taken into account in a multistage DNEP question in ref. [82], thus the method of artificial bee colony (ABC) was adopted.

The integration of renewable energies with electric power system can not only be in a large-scale, but also be in a small-scale, known as the integration of distributed generations (DGs) to some extent. The former often causes uncertainties in TNEP, as what mentioned in section 6.1, while the latter can cause uncertainties in DNEP, and also flexible operation modes in distribution network, such as grid-connected model and islanded mode of microgrids. A relatively systemic planning model for distribution system with DGs was presented in ref. [83], with consideration of DG reactive capability limits. In this paper, probabilistic models were employed to describe the uncertainties of load demand, wind speed and solar radiation, thus the methods of TRIBE particle swarm optimization (TRIBE PSO) and ordinal optimization (OO) were presented to deal with the optimization problem and its sub-problems. Based on a certain microgrid, an energy management method was used to conduct a determinist operational planning in ref. [84]. Energy managing of both central level and local level within a microgrid were considered and analyzed, respectively. Ref. [85] studied the effects of microgrids on electric distribution system, with the proposed methodologies concerning microgrid modeling and network planning algorithm. The cases and results covered the comparison of backup philosophies and the comparison of conventional distribution networks without microgrids and with a significant (33%) penetration of microgrids. In a summary, when related with DGs and microgrids, there are many interesting points to research under the topic of DNEP.

7 Conclusions

The smart grid with integration of renewable energies is the possible future electric power system. Focusing on them, new ideas and new methods may come up to deal with the related challenges and uncertainties. This paper chooses six subjects to summarize the recent advanced work on smart grid and renewable energy integration, in order to present an overview of new progress in related areas and to help relative researchers find promising spots. Besides the topics mentioned in this paper, there are still some other challenging and interesting problems to be solved.

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