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Introduction

1.1 Power Grid and Natural Disasters

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The electric power grid is the largest and most complex machine in the world. It is employed to supply, transfer, and utilize electric power. Its history can be traced back to 1881, when the world's first power system was built at Godalming in England. In the twentieth century, electricity had gradually become one of the basic necessities in the modern society. The power grid has been performing effectively in satisfying the energy need and, meanwhile, has been causing adverse impacts on the natural environment. The associated carbon emissions also contribute to the climate change that has been causing more frequent natural disasters.

In Asia and the Pacific, the primary energy demand is estimated to have more than 2.4% increase each year by 2030, while typically the electricity demand has a higher increase, at about 3.4%. For the increased electricity demand, it is desired to have an efficient and reliable power supply. In recent years, the economy, society, and environment have also introduced new pressures or requirements on power grids, e.g. shifting from centralized to decentralized structures. Hence, long-term sustainability of power grids is of critical importance in developing the twenty-first century power grids, i.e. smart grids.

A power grid usually covers a wide geographical region, and many of its components in the system are exposed to the external environment, which makes the power grid vulnerable to natural disasters, e.g. wind storms, ice storms, thunderstorms, earthquakes, wildfires, hurricanes, and flooding [1–3]. In recent years, more frequent natural disasters have resulted in severe power outages that are large-scale and long-duration. For example after the Hurricane Sandy struck the East Coast of the United States in 2012, approximately 8.35 million customers were

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reported without power [4]. Some studies have indicated that the climate change leads to the increase in disastrous events. The global temperature rise has been considered as one of the important underlying causes of disastrous events with higher intensity and frequency [4, 5].

Disastrous event-related power outages have introduced tremendous economic losses and significant life risks, highlighting the importance of enhancing power grid resilience [6], which generally refers to the ability to withstand and rapidly recover from disruptive events [7, 8]. A natural disaster can inflict widespread and severe damages to the power grid, leaving numerous customers without power for days, sometimes even for over a week. One of the critical requirements on resilient power grids is that the system can effectively prepare for, response to and recover from natural disasters, as most social activities greatly depend on the reliable power supply [9].

Aside from external natural disasters (e.g. weather-related events), the cyber systems, which enable system operators to efficiently monitor and control the power grid, make the system vulnerable to cyber intrusions. Conventional strategies, e.g. common preventive and emergency measures, due to their little consideration of weather-related and cybersecurity-related events, fail to be resilient preparedness, response, or recovery strategies. Considering potential weather-related events attacking the physical system and cybersecurity-related events attaching the cyber system, resilient power grids have to be constructed.

In this chapter, the definition and importance of power grid resilience will be introduced. Then, challenges brought by different kinds of events that may jeopardize resilient power grid operation will be discussed, and the corresponding resilience enhancement strategies will also be discussed.

1.2 Power Grid Resilience

1.2.1 Definitions

As mentioned above, sustainable power grids have to balance economic growth and social progress, meanwhile, preserving the natural environment [10]. With more frequent severe power outages caused by natural disasters, power grid resilience is receiving much attention. Resilience can be generally understood as the ability of power grids to avoid or reduce failures and to recover quickly after failure occurrence [11]. Currently, there is not a unified definition of power grid resilience. Several definitions given by different organizations are shown as follows:

- In [12], the U.S. National Academies of Sciences, Engineering, and Medicine define resilience as “the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events.”

- In [13], the Cabinet Office of the United Kingdom refers to resilience as "the ability of assets, networks and systems to anticipate, absorb, adapt to and/or rapidly recover from a disruptive event."
- In [14], the U.S. President's National Infrastructure Advisory Council specifies resilience as "the ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event."
- In [15], the IEEE Power and Energy Society Industry Technical Support Task Force prescribes resilience as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."
- In [8], the U.S. Electric Power Research Institute states that "grid resilience includes hardening, advanced capabilities, and recovery/reconstitution."

Although the resilience definitions given by different organizations are different, the key understanding that decision-makers should plan for, ride through, and recover from each potential disastrous event is consistent. According to the goals of enhancing power grid resilience, a sequence of resilience merits, including robustness, resourcefulness, rapid recovery, and adaptability, have been highlighted [16, 17]:

- *Robustness prior to an event*. This necessitates that the grid is capable of remaining to stand and operate in the face of extreme events. For instance, hardening a grid's critical structure, from a mid- or short-term perspective, can be performed to guarantee a strong system prior to an event. In addition, to ensure the robustness, investments, and maintenance scheduling of critical electric devices, from a long- or mid-term perspective, can be entailed prior to weather-related and cybersecurity-related disastrous events.
- *Resourcefulness during an event*. This requires skillful abilities to manage the power grid when a disruptive event unfolds. Effective and real-time strategies are expected to be implemented to mitigate the negative impacts. For instance, determining what should be conducted to mitigate the damages is a critical issue during a disastrous event. Furthermore, adequate resources for communications among different decision-makers are important in implementing established mitigation strategies.
- *Rapid recovery after an event*. This demands the ability to recover the power grid back to a normal state quickly after adverse events. For example, detailed recovery plans under the conditions of various blackouts should be established in time and adequate resources for implementing the recovery strategies should be guaranteed.
- *Adaptability to future events*. This denotes the ability to absorb new lessons from past events and generalize to new situations. Instead of case-by-case methods, more flexible measures and strategies are necessary to be fitted into various situations as well as to improve the power grid's capability of dealing with extreme events.

1.2.2 Importance and Benefits

As power grids are critical infrastructures for social and economic development [12], a power outage might cause severe consequences. The U.S. National Research Council [12] and the U.K. House of Lords [18] have emphasized the importance of resilient power and energy infrastructures. The North American Electric Reliability Corporation [14, 19, 20] and the U.S. Electric Power Research Institute [21] have further recognized the functionalities of power grid resilience. In general, enhancing power grid resilience can improve economic, social, and environmental sustainability.

Note that a reliable power grid is not necessarily resilient. Specifically, power grid reliability guarantees its operation under normal-state conditions, or in high-probability, low-impact events. On the other hand, a resilient power grid is capable of performing well in low-probability, high-impact events such as natural disasters [12]. Many resilience-oriented power grid planning and operation strategies have been proposed and studied in the literature. Nevertheless, many problems, including distribution grid automation to enhance the restoration capability and the utilization of mobile generation resources which involve the consideration of road networks, have not been addressed.

In the following, the importance and benefits of power grid resilience are briefly discussed from three perspectives.

1.2.2.1 Dealing with Weather-Related Disastrous Events

As mentioned above, electric power grids have the characteristic of wide geographical coverage, making grid components exposed to extreme weather events such as tornadoes, typhoons, windstorms, hurricanes, and blizzards. These disastrous weather events are major causes of power outages. In addition, the aging nature of electric devices also makes power grids more susceptible to extreme weather events. For instance, about 679 power outages were caused by weather events from 2003 to 2012 in the United States, and each event affected at least 50 000 customers [8].

Table 1.1 shows the number of blackouts between 1984 and 2006 in the United States [22]. As indicated, around 44% of the outage events were weather-related. Based on the analysis of the U.S. President's Executive Office, weather-related outages lead to about $25 billion in economic losses annually. In addition, weather-related outages have an increasing trend [8].

To sum up, outages induced by weather-related disastrous events happen more frequently all around the world, causing significant economic and safety damages to the human society. With the advancement of power grids, this type of extreme weather will incur greater risks to various security issues, making it an urgent task for each country to improve the power grid resilience against such disastrous events. As aforementioned, improving power grid resilience in terms of

Table 1.1 Outages in the United States for 1984–2006.

Cause	Percentage of events	Mean size in MW	Mean size in customers
Earthquake	0.8	1408	3 75 900
Hurricane/tropical storm	4.2	1309	7 82 695
Lightning	11.3	270	70 944
Wind/rain	14.8	793	1 85 199
Ice storm	5	1152	3 43 448
Tornado	2.8	367	1 15 439
Other cold weather	5.5	542	1 50 255
Fire	5.2	431	1 11 244
Intentional attack	1.6	340	24 572
Supply shortage	5.3	341	1 38 957
Other external causes	4.8	710	2 46 071
Equipment failure	29.7	379	57 140
Operator error	10.1	489	1 05 322
Voltage reduction	7.7	153	2 12 900
Volunteer reduction	5.9	190	1 34 543

the handling of weather-related disastrous events can significantly enhance the economic, social, and environmental sustainability.

1.2.2.2 Facilitating the Integration of Renewable Energy Sources

Renewable energy sources (RESs), including but not limited to wind turbines and photovoltaic panels, have been integrated into power grids worldwide at an increasing rate. Their effects in relieving the energy crisis concern are promising. However, the variable and uncertain natures of RESs have introduced new challenges to power grid planning and operation and brought about new issues to power grid resilience. Conventionally, the power grid consisted of controllable generators and semipredictable electric power demands. Thus, power grid operators could just adjust generation sources to accommodate admissible deviations of power demands. Now with the growing RES integration, such an operation paradigm becomes ineffective. New operating strategies utilizing smart grid technologies, e.g. advanced optimization methods, are needed, so that power grid resilience regarding the integration and utilization of RESs can be improved.

To generate operation strategies with both robustness and economy, stochastic optimization and robust optimization have been applied to cope with the uncertainty of wind power. With probability distribution information of uncertain parameters, stochastic optimization is a mature methodology to provide decisions against uncertainties. To name a few, stochastic unit commitment and stochastic economic dispatch models were proposed in [23, 24]. Nevertheless, an accurate probability distribution of unknown parameters can be quite difficult to identify [25]. In this regard, robust optimization is a promising alternative receiving much attention in recent years, partially because it does not require accurate distribution information of uncertainties. It evaluates the worst-case performance of a decision, resulting in an optimization solution that is robust against any possible scenario in the uncertainty set.

However, to build resilient power grids with high penetration of RESs, many critical problems, e.g. restoration of transmission grids with large-scale RESs, have not yet been addressed.

In general, RESs can empower more flexible strategies for improving power grid resilience, but we must also consider the impact of RESs' characteristics on the power grid. Reaching a fair balance between RES integration and resilience improvement in power grid is critical for relevant research. In fact, only with resilient strategies that sufficiently mitigate the adverse impacts of RESs, the economic, social, and environmental benefits of RESs can be fully utilized.

1.2.2.3 Dealing with Cybersecurity-Related Events

The former two parts are mainly about security and resilience of the physical system of a power grid. Apart from that, security of the cyber system is also an important part of power grid resilience. The reliable operation of modern power grids is fundamentally supported by cyber systems. The devices that monitor and control power grids are typical information and communications technologies-based systems. Those systems face the threats of cyber-attacks, which can undermine the control systems and endanger the secure operation of power grids.

In recent years, cyber-attacks have resulted in many security problems. The U.S. National Security Agency has reported that there have been some cyber intrusions to critical infrastructures and has emphasized the importance and benefits of improving the resilience of cyber systems. The following shows several reported incidents of cyber intrusions into existing information and communications technologies-based systems [26]:

- *BlackEnergy*. It was first reported in 2007, with critical energy infrastructures being its targets. In 2014, several information and communications technologies-based systems were infected by BlackEnergy. With BlackEnergy, cyber-attackers can deliver some plug-in modules for audio recording, keylogging, and grabbing screenshots, etc.
- *HAVEX*. For the early version of HAVEX, it was distributed through spear-phishing attacks or spam e-mails. After several revisions, HAVEX

has become a Trojan horse used to modify "legitimate" software in information and communications technologies-based systems including the supervisory control and data acquisition (SCADA) system, and supervisory control and data acquisition (SCADA) systems by adding additional instructions to codes.

- *Sandworm*. It is a Trojan horse, which is used to deliver malware on thumb drives.

As indicated by the aforementioned events, cyber-attacks cannot be neglected. With the development of cyber networks, cyber security of power grids faces new threats from attacks that are very stealthy and less expensive. Therefore, the cyber security in power grids is currently a hot topic in resilience research. For example in [27], a novel criterion for assessing the resilience of power supply to data centers was proposed to evaluate the system's capability of sustaining functionality during an outage. Enhancing the cyber system resilience of power grids not only mitigates the threats from cyber-attacks but also enables the cyber system to more effectively and more efficiently monitor and control power grids.

1.2.3 Challenges

Conventional strategies, e.g. common normal state-based preventive and emergency strategies in the planning and operation timescales, fail to consist of resilient measures against disastrous events, as they have little consideration of such low-probability, high-impact events either weather-related or cybersecurity-related. Since power grid resilience requires robustness, resourcefulness, rapid recovery, and adaptability at different stages, appropriate and sophisticated strategies of different stages should be implemented [28]. Furthermore, complicated characteristics of modern power grids, from the perspectives of the source, network, storage, and load, pose great challenges to the construction of resilient power grids.

In the following, some challenges to improving power grid resilience are briefly discussed:

- *Component reliability enhancement*. Electric power companies try to maximize their profits and maintain a good system technical behavior from the reliability perspective. As a weather-related disastrous event unfolds, the critical devices on the trajectory of the event are expected to have high reliability, which can reduce the probability of being in failure and therefore ensure system resilience [29]. In this regard, component reliability enhancement, e.g. maintenance scheduling in consideration of potential extreme events, is needed to guarantee good conditions of electric devices. Establishing a comprehensive maintenance plan considering potential natural disasters is not an easy task. The following challenges should be considered: First, weather-related events occur with uncertainties, and the influences of those events on the deterioration of each component are stochastic. Second, the dimension of enormous electric devices in power grids results in large-scale optimization problems. For short-term maintenance scheduling, many system operation constraints, including the $N - 1$ security, ramping rates of generating units, power balance, and spinning reserve capacity requirements, should also be considered. The relevant optimization models are usually computationally intractable with large-scale systems [30]. Third, considering a fast growth of renewable energy in power grids, the influences of uncertainties of renewables on maintenance scheduling considering weather-related extreme events are critical issues. To tackle those problems, proactive operation strategies to enhance system resilience considering the uncertain sequential transitions of states are needed.

- *System state acquisition*. System state acquisition is a prerequisite for power grid operators to perform resilient, proactive, and emergency strategies, before the extreme event, during its unfolding, and after its occurrence [31]. Facing extreme events, a system is under continuous and severe disturbances. In this regard, the dynamic states of the system should be identified. Measurements from phasor measurement units (PMUs) are rapidly updated and can be employed to perform dynamic state estimation [32]. Performing dynamic state estimation should consider the following challenges. First, multiple control areas, resulting from the power industry's deregulation, should be considered. These interdependent areas usually do not share all information of their own control areas. Second, appropriate approaches for estimating dynamic states are needed. Currently, some approaches can be used for estimating dynamic states with the assumption of Gaussian distributions of measurements' noises [33, 34]. However, some measurements' noises are not satisfied with the assumption of Gaussian distributions. Third, a rapid computation speed for dynamic state estimation is required.
- *Multiple energy systems*. It is expected that power grids have more contributions to the sustainability and low-carbon development of energy sectors. In China, carbon neutrality is an essentially important target, and a series of policy measures have been implemented to reduce greenhouse gas emissions. By means of integrating different energy sources across different pathways, the multi-energy system provides a promising way to reduce carbon emissions. However, the multi-energy system has more complicated characteristics compared to traditional power grids, and in consequence needs sufficient and novel measures to guarantee high system resilience. In 2021, one severe power outage occurred in Texas, partly due to inappropriate operation of the multi-energy system in the face of extreme cold weather. In fact, different energy carriers of the multienergy system have different responses to disturbances, and this leads to difficulties in constructing coordinated strategies. Therefore, it is a challenge

for multiple energy systems to construct systematic frameworks and techniques that enhance system resilience.

- *Renewable energy uncertainty*. With increasing concerns on possible energy shortage, worldwide efforts have been carried out to integrate enormous RESs into power grids [35]. Among different kinds of renewable energy, wind power attains the highest penetration in some countries, partially owing to the relatively mature wind turbine technologies. Although wind power is promising in easing the worries over the energy crisis, its variability and uncertainty have brought about great challenges to the reliable and economic operation of power grids. Other kinds of renewable energy also possess variability and uncertainty features, which also impose similar challenges and worsen relevant problems. Two critical issues need to be considered when a power grid is under the threat of a natural disaster, especially an extreme weather event. The first one is that the extreme weather event has a great impact on renewable generation, and the second one is that the grid in the face of the event may not be as strong as that under normal conditions. These two critical issues make conventional strategies improper to the resilient operation of high-renewable power grids against extreme weather events. In addition, RESs such as photovoltaic power and wind power are usually connected to the grid via power electronics devices with low inertia, which reduces the grid strength against disturbances. The abovementioned factors pose great challenges to resilient high-renewable grid operation in the face of natural disasters.
- *Cyber-physical systems*. Many research studies focus on power grid resilience from the perspective of physical systems. However, information and communications technologies have been playing important roles in physical system monitoring and control and have driven the conventional power system into the cyber-physical system. Many components in the cyber-physical system are directly exposed to external environment, and they are both vulnerable to natural disasters (including extreme weather events) from the perspectives of the security and resilience of information networks and physical networks. If a cyber-physical system is affected by an extreme weather event, unavailability of some parts of the cyber system might result in incomplete information, which in consequence can lead to failed state estimation and large control errors. Therefore, how to analyze and mitigate the impacts of disastrous events on cyber-physical systems is a critical challenge with regard to power grid resilience improvement.
- *Multi-area networks*. The development of power markets, multiple energy systems, and system expansion, etc. have been driving power grids into multi-area interconnected systems. Conventional centralized strategies usually cannot be directly employed for multi-area interconnected systems when considering specific jurisdictional mandates, extensive communication burdens,

and information privacy, etc. Boundary restrictions between different energy systems complicate the interaction problems and coordinated strategies and result in challenges to the improvement of system resilience.

Note that other than the abovementioned issues, many other challenges need to be addressed in building resilient power grids. Relevant discussions are included in relevant parts, where appropriate, of this book.

1.3 Resilience Enhancement Against Disasters

A power grid resides in different stages when it is exposed to natural disasters including extreme weather events. It is necessary to define these stages to enable systematic enhancements of power grid resilience against these events. In October 2010, the U.S. President's National Infrastructure Advisory Council released a report presenting a resilience structure with four features, based on the sequence of "prior to an event," "during an event," "after an event," and "postincident learning," respectively [14, 16, 17]. Building effective resilience enhancement strategies requires an understanding of preventive, real-time and recovery strategies, and an awareness of how the related actions impact grid planning and operation [36].

Specifically, prior to an event, "robustness" requires the grid to stay standing or keep operating in the face of the event that can be catastrophic. Strengthening and hardening the system is one of the acceptable preventive strategies. In general, maintaining and investing in critical infrastructure elements can improve grid robustness so that the system can withstand those extreme events. During an event, "resourcefulness" requires that the grid has sufficient capabilities of managing the event as it unfolds. In this stage, it is necessary to identify available strategies and prioritize what can be implemented to mitigate the impact of damages caused by the event. After an event, it is desired that we can get the system back to its normal state as quickly as possible. To this end, determining emergency and restoration approaches is important, and scheduling appropriate resources and right people to right places is also critical [37, 38].

1.3.1 Preparedness Prior to Disasters

Prior to natural disasters, assessments and preventive strategies need to be implemented to improve the power grid's capability of dealing with the events, such as state assessments using historical data-based models [39–41], and resilience enhancement strategies based on distributed generation (DG) allocation [42], microgrid technologies [43, 44], and switch placement [45]. Overall, methods of enhancing power grid resilience can be divided into component level and system level. A brief discussion is provided in the following:

1.3.1.1 Component-Level Resilience Enhancement

Good conditions of electrical devices are important for power grid resilience enhancement. Usually, maintenance activities are employed to mitigate the deterioration of grid components. However, such activities often increase the total operating cost of grids. To achieve an appropriate trade-off between grid resilience and operating cost, system operators need to develop a series of combined long-, mid-, and short-term maintenance activities for various components in the power grid.

Currently, different categories of maintenance scheduling methods, e.g. planned maintenance scheduling, condition-based maintenance scheduling, reliability-centered maintenance scheduling, and optimization-based maintenance scheduling, can be implemented to improve grid resilience:

- *Planned maintenance scheduling*. In planned maintenance scheduling, each maintenance event is prescheduled, and all future maintenance events are preprogrammed. Different maintenance events implemented on different devices are programmed separately according to legislation or manufacturer recommendations. Its advantages include the easiness of scheduling and programming maintenance events, evenly distributed costs, and low costs of instruments used for supervision of devices. It surely also has disadvantages, such as requirements for ongoing labor costs and training investment, and very expensive operation because of frequent changes of parts.
- *Condition-based maintenance scheduling*. Condition-based maintenance scheduling means that maintenance tasks are only performed when it is necessary according to equipment conditions [46]. One prerequisite is having the capability of monitoring the equipment's health, i.e. condition monitoring. The developments in sensor technologies, signal processing, and online diagnosis empower system operators to have access to more accurate conditions of grid components, e.g. generating units [47] and transformers. Among current research, the Markov model-based methodology is a promising tool for improving condition-based maintenance scheduling. Existing studies have shown that Markov models are useful for establishing effective and efficient maintenance scheduling [48–56].
- *Reliability-centered maintenance scheduling*. Reliability-centered maintenance scheduling is a well-organized method by which the maintenance processes aim to improve system reliability. It was introduced into the power engineering field after its successful deployment in the aerospace and aircraft industry in the 1960s [57]. Relevant studies focused on voltage regulators [58], circuit breakers [59], overhead lines [60], underground systems [61], and power

transformers [62]. The advantages of reliability-centered maintenance scheduling is that it has the ability to minimize the frequency of overhauls and increase the reliability of system components [63, 64].

- *Optimization-based maintenance scheduling*. Optimization-based maintenance scheduling refers to methods that formulate the maintenance scheduling problem as an optimization model and solve it by optimization algorithms. For example, using integer programming or mixed-integer programming methods, the statuses of electric devices are modeled as binary decision variables. When a device is scheduled for maintenance, the value of its associated variable regarding the device status is 0; otherwise, the value is 1. As the operating conditions of power grids should be satisfied under maintenance events, security-constrained optimal maintenance scheduling, associated with unit commitment constraints and $N-1$ security constraints, should be considered [65, 66].

1.3.1.2 System-Level Resilience Enhancement

Apart from component-level resilience enhancement, the system-level improvement of grid resilience is also essential. Prior to disastrous events, outage evaluation and proactive preparedness are the main methods to make power grids less susceptible to damages caused by disasters.

With sufficiently accurate outage predictions, power grid operators can pre-allocate repair personnel and components for the following restoration after the disaster. Other proactive strategies can also be implemented based on available predictions. Current studies regarding outage predictions mainly focus on data-based statistical models [39–41, 67, 68]. Though performing well in some specific service areas, they may suffer from poor scalability and generalizability.

Regarding proactive strategies, the extension and hardening of power grids, such as adding DGs, adding redundant lines and hardening existing electric devices [42], are effective approaches recommended by the U.S. Department of Energy. Decision-makers also have to determine how to allocate and mobilize available resources to guarantee timely responses and recovery efforts against possible damages [69–71], so as to improve the grid resilience.

1.3.2 Response as Disasters Unfold

During disastrous events, power grid operators need to monitor the condition of each system component and the overall system's operating state, schedule repair groups to secure critical facilities, and dispatch existing system components such as generators, relay protection devices, and transformers to maintain voltage and frequency balances. Specifically, some real-time strategies are expected to be performed to mitigate the negative impacts of disaster-induced damages. Relevant research includes state acquisition [72], controlled separation [73], and microgrid sectionalization [74], etc. The benefits of these measures are noticeable. That is, they lower the blackout risk while maintaining regular system performance. A brief discussion on major measures is provided in the following.

1.3.2.1 System State Acquisition

Acquiring states of the power grid, by state estimation, etc. is a prerequisite for monitoring and controlling the system. Without it, responsive strategies as the extreme event unfolds cannot be established during the event. In general, measurements such as transmission line power flow in the SCADA system have slow update rates, and conventional state estimation methods based on steady-state models of a system can only attain the static states. On the other hand, measurements from PMUs are rapidly updated and can be employed to perform dynamic state estimation. In addition, to achieve smart features such as demand response in smart grids, more accurate models and more rapid algorithms are critically needed for state estimation of distribution grids. Selected categories of state estimation are briefly discussed as follows:

- *Static state estimation*. Static state estimation is mainly to determine the system's steady-state status, e.g. bus voltages, based on measurements at each short-term time slot. Specifically, it translates telemetered data into a reliable estimate of transmission and distribution network topology and status. For relevant analyses, lots of algorithms have been designed for solving static state estimation problems, such as the weighted least squares algorithm [75], parallel computation algorithm [76], and interior-point based algorithm [77], etc. However, natural disasters including extreme weather events are considered as severe disturbances where static state estimation methods might only have quite limited usefulness and effectiveness.
- *Dynamic state estimation*. With increasing disturbances in the power grid, e.g. from wind power and solar power, dynamic characteristics of the system are crucial for operators to implement control actions and ensure system stability. As PMU measurements are updated rapidly, their measurements can be employed for dynamic state estimation, concerned with the tracking of system states with more often and fast changes. The extended Kalman filter is one of the effective methods for conducting dynamic state estimation [78–80]. Based on a relevant IEEE standard [81], PMU can provide measurements at the rate of up to 120 samples per second, while in practice, the rates of PMU measurements may be much lower, e.g. 30 samples per second. To estimate dynamics accurately under the condition of lower measurement rates, algorithms based on the extended particle filter [82–84] were proposed, which can improve the robustness of dynamic state estimation.

- *Multi-area state estimation*. Multi-area state estimation primarily tackles the issue of performing efficient state estimation on large power grids. One objective is to decrease the computation time, which helps take advantage of real-time measurements gathered within multiple areas across the system. Specifically, multi-area state estimation is based on a selected type of decomposition-coordination framework, which takes use of weaker geographical or measurement connections across regions, in conjunction with well-established solution approaches. With more PMUs in power grids, there have been many research studies focusing on multiarea state estimation [85, 86]. In general, there are two computation architectures for multiarea state estimation, i.e. the hierarchical architecture [72, 87] and the decentralized architecture [88, 89].

1.3.2.2 Controlled Separation

Currently, power girds in near areas are often connected together to construct an interconnected power system, which ensures efficiency, enhances reliability, and improves resilience against some issues. However, under the condition of some rare circumstances, e.g. extreme weather events and man-made incorrect operations, different groups of generators in an interconnected system may be unsynchronized. If emergency controls [90, 91] cannot terminate the unsynchronization among different groups of generators, the controlled separation strategy, i.e. disconnecting some lines to divide an interconnected system into several separated grids, might need to be performed to prevent cascading failures and blackouts.

For an interconnected power system, coherent groups of generators usually exist [92–94]. Generators in a coherent group are usually synchronized, and these generators should be included in one separated system. The grouping of generators after large disturbances can be considered as an NP-hard partition problem from the perspective of mathematics. Many methods, e.g. geometric methods [95–97], combinatorial methods [98, 99], and spectral methods [100, 101], can be used.

Then for controlled separation, various strategies have been proposed to solve this power system partitioning problem. When selecting the optimal splitting strategy, the minimum load-generation imbalance is a critical criterion, which partly determines the splitting lines. This criterion aims to ensure that the frequency of each separated system is within the acceptable range. Most of the relevant research studies have not considered the constraints of reactive power balance. Reactive power determines the voltage profile, and its imbalance may result in voltage instability [102]. For example insufficient reactive power in the Idaho area of the United States on 2 July 1996 resulted in a blackout [103]. Therefore, it is necessary to include both real power balance and reactive power balance when establishing a splitting strategy.

1.3.3 Recovery After Disasters

Even though many preventive preparedness and proactive response actions can be performed prior to and during a disastrous event, it is generally impossible to completely avoid outages. When outages occur after the event, it is necessary to recover the electric service as quickly as possible to improve the system resilience.

The recovery of a power grid after a partial or total failure is a complicated procedure. Many aspects must be considered, including the system's operational condition, equipment availability, and restoration time, etc. A conventional power grid recovery plan usually includes three stages, i.e. preparation, system restoration, and load restoration [104–106] (especially for the transmission grid). However, there are unique characteristics associated with outages caused by natural disasters, leading to different requirements on the recovery strategies. New approaches, such as microgrid-based restoration strategies [107] and decentralized restoration schemes [108], are needed. Moreover, power grid recovery is a multi-objective, multi-stage, multi-variable and multi-constraint optimization problem with nonlinearity and uncertainty. Effective and efficient algorithms are needed to find the optimal recovery plan.

In the following, several issues on postdisaster grid recovery are briefly discussed.

1.3.3.1 Conventional Recovery Process

How to quickly recover a power grid following a partial or complete blackout is a significantly challenging task. There have already been many research studies focusing on conventional power grid recovery methods. As mentioned above, a typical power grid recovery process includes three stages, i.e. preparation, system restoration, and load restoration:

- *Preparation stage*. The preparation stage is mainly to assess the grid's state and identify critical loads and initial cranking sources.
- *System restoration stage*. In the system restoration stage, the main objective is to establish a strong bulk power network by restarting appropriate blackstart and nonblackstart generating units associated with appropriate transmission lines and some critical loads [105, 106].
- *Load restoration stage*. In the load restoration stage, the main objective is to restore as many loads as possible. This stage is performed after a sufficiently strong bulk power network is established to maintain the system frequency and voltage profiles. Many approaches, e.g. expert systems [109, 110], fuzzy logic [111, 112], heuristic approaches [113, 114], and mathematical programming [115, 116], have been employed for decision-making in load restoration.

Note that the above recovery approaches are typically adopted by transmission grids. However, the effectiveness of conventional restoration approaches for post-disaster recovery might be limited. More proactive preparedness measures prior to the extreme event are needed. Moreover, as the grid might have been separated into subgrids by the damages induced by the disaster, the nesting of system restoration and load restoration is much more complicated. In general, novel and effective recovery methods need to be developed for enhancing grid resilience against disastrous events.

1.3.3.2 Microgrids for Electric Service Recovery

For integrating distributed energy resources, etc., microgrid technologies have been extensively adopted in power grids. In this regard, using microgrids for electric service recovery is becoming critically important and has received increasing attention.

Reference [117] studied voltage and frequency controls in the blackstart restoration of microgrids. In [118], an algorithm for identifying the automatic switching time was proposed for restoring microgrids. Reference [119] modeled microgrids as virtual feeders and applied spanning tree search algorithms to find the strategy maximizing restored loads and minimizing the number of switching actions. Reference [74] proposed to optimally sectionalize a distribution grid into networked self-adequate microgrids for continuously providing reliable power supply for the maximum loads. In [120], based on the continuous operating time concept, the availability of microgrids for critical load restoration and the service time were evaluated to enhance power grid resilience. More detailed literature reviews can be found in [121] and [120], etc.

The above works assume the microgrids to be installed beforehand, which may not be available at the current stage in many places. Followed by [122] and [123], etc., reference [121] is the first to temporarily form microgrids with DGs to continue supplying critical loads after a disastrous event. This microgrid formation strategy can be further extended as the dynamic microgrid formation strategy, which dynamically changes the boundaries of temporarily formed microgrids according to the system's state changes. Moreover, instead of fixed DGs, mobile power sources can also be applied in microgrid formation for electric service recovery.

As mentioned above, novel power grid recovery approaches including the above ones are needed by systems endangered by natural disasters. Also note that both transmission and distribution grids may adopt the above system recovery methods.

1.3.3.3 Distribution Grid Topology Reconfiguration

Topology reconfiguration (or called network reconfiguration) is an essential measure of power grids for many different objectives. For example, the above microgrid formation-based restoration strategy needs to conduct topology reconfiguration. As distribution grids are typically built with quite smaller levels of redundancy compared with transmission grids, topology reconfiguration is a critically important and must-used strategy in electric service recovery of power distribution systems.

Both static network and dynamic network reconfigurations have been investigated by the research community. For instance, the microgrid formation problem studied in [121–123] is essentially a static network reconfiguration. As for dynamic network reconfiguration of distribution grids, it often relies on the real-time operation of remote-controlled switches. The effects of hourly distribution network reconfiguration on power loss reduction and operation cost minimization were investigated in [120, 124–127], some of which considered DGs. Specifically, reference [124] studied segmented-time reconfiguration coupled with DGs' reactive power control to minimize the distribution grid operation cost. In [127], hourly reconfiguration in the presence of RESs was studied based on mixed-integer, second-order cone programming to minimize daily network losses. In [120], to minimize power losses, a hierarchical decentralized agent-based dynamic network reconfiguration methodology was presented.

Some other studies applied dynamic network reconfiguration to DG integration in a more straightforward manner, i.e. minimizing DG curtailment or maximizing DG penetration. In [128], it is demonstrated that using hourly distribution network reconfiguration can significantly reduce both wind and solar DG curtailments for systems with high DG penetration. In [129], where DG penetration maximization was studied, results showed that distribution network reconfiguration can mitigate the over-voltage problem caused by the increased DG penetration. In [130], with a mixed-integer nonlinear multiperiod optimal power flow model, both static and dynamic reconfigurations were adopted to improve DG hosting capacity, and the results suggested that integrating larger amounts of DGs can be achieved by a small number of line switching actions. To reduce network losses in grid-connected operation and load curtailments in islanded operation, microgrid optimal scheduling with dynamic network reconfiguration was studied in [131]. More detailed literature reviews on distribution grid dynamic network reconfiguration can be found in [130, 132, 133] etc.

In summary, the effectiveness of distribution network dynamic reconfiguration in enhancing distributed renewable energy integration has been studied extensively, mainly from two aspects, i.e. using it to explicitly minimize the curtailment of existing DGs or maximize the penetration of DGs to be accommodated, and using it to mitigate DGs' negative impacts on the considered objectives and constraints.

However, the utilization of more flexible and more adaptive distribution network reconfiguration for postdisaster recovery of distribution grids has received somewhat less attention. For example distribution network reconfiguration greatly relies on the deployment of remote-controlled switches, which are highly expensive, and their massive deployment is not likely in the near future. Therefore, minimizing installation and maintenance costs of remote-controlled switches while achieving certain reconfiguration requirements are an important research topic. It has been studied mostly for the purpose of reliability improvement [134–136], but quite less explored considering the recovery of distribution grids after extreme events.

Also note that distribution grids mostly have to operate in a radial topology. Therefore, radiality constraints need to be considered in most relevant optimization problems. However, existing formulations of radiality constraints might implicitly impose restrictions on the flexibility that can be considered by the optimization models. To deal with such current shortcomings, a new formulation of radiality constraints for reconfiguration-related optimization problems that fully enables the topological and related flexibility of distribution grids is necessary.

1.4 Coordination and Co-Optimization

Coordination and co-optimization have become essential issues for power grid resilience enhancement against natural disasters for many reasons. To name a few, first, the damages caused by disastrous events are typically large-scale and long-duration, so the available resources need to be coordinated and co-optimized in their utilization. Second, different from common single-fault outage scenarios, the outages induced by extreme events can lead to significant economic losses, so more proactive preparedness measures, more timely response actions, and more effective recovery efforts need to be coordinated and co-optimized for mitigating the impacts. Third, a disastrous event can cause damages and outages to different subgrids in an interconnected power system, so the coordination and co-optimization among different areas are essentially necessary.

Selected issues, some aforementioned, regarding the coordination and co-optimization in power grid resilience enhancement against disastrous events, are briefly discussed as follows:

- *Different stages*. As mentioned above, resilience enhancement strategies are implemented in three different stages, i.e. prior to the event, as the event unfolds, and after the event. Coordination and co-optimization among different stages are critically necessary. First, preparedness measures before the event need to consider the flexibility needs of the power grid during and after the event. Second, response actions as the event unfolds might have to take into account the actions' impacts on the system's postdisaster state. Third, some postdisaster recovery efforts might result in permanently installed flexibility resources, etc. Therefore, the effectiveness of those efforts in the prior-event preparedness measures of future disasters needs to be evaluated.

- *Various flexibility resources*. In preparing for, responding to and recovering from a disastrous event, various flexibility resources might be available. Although the power grid operator understands the potentially significant impacts of such extreme events and provides lots of emergency resources, they still need to be coordinated and co-optimized, so that they can be fully utilized. For example, for distribution grid restoration and recovery, the dispatch of flexibility provided by mobile power sources, repair crews, remote-controlled switches, and DGs, etc. needs to be coordinated and co-optimized. Their utilization also needs to be coordinated and co-optimized among different stages mentioned above.
- *Transmission and distribution grids*. Both transmission and distribution grids are endangered by extreme events. That is, disaster-induced damages happen in both of them. Moreover, flexibility resources disperse in both of them. Therefore, resilience enhancement strategies often need to coordinate and co-optimize both levels of power grids. For example, if the transmission grid experiences a partial or complete blackout due to the disaster, cranking power provided by distribution grids can greatly reduce the transmission grid's restoration time. In fact, whether a bottom-up approach, a top-down approach, or a mixed one should be used is an important issue in the postdisaster recovery of transmission and distribution grids.
- *Multiple areas*. As mentioned above, a natural disaster typically impacts a large geographical area covering an interconnected power system. Therefore, in different stages and when using various flexibility resources, multi-area issues need to be dealt with. First, the interimpacts among different areas need to be mitigated. For example, the blackout of a subgrid might result in the loss of some tie-line power, which further leads to negative influences on other subgrids. Second, the interassistance among different areas needs to be utilized. For example repair crews of different subgrids can be coordinated and co-optimized, so that the recovery of the interconnected power system is enhanced, which improves the resilience of individual subgrids.
- *Cyber and physical systems*. With the development and applications of smart grid technologies, power grids have become a systematic integration of cyber and physical systems. Disastrous events not only impact physical parts of a power grid but also affect its cyber parts. In many cases, power grid resilience enhancement approaches have to consider both cyber and physical systems. For example, in prior-event preparedness, other than hardening the power

lines, etc., the communications system also needs to be strengthened, as state acquisition is critically important in responding to and recovering from the extreme event. In fact, when recovering a power grid, in some cases, some physical parts need to be repaired first to restore the power supply to critical cyber systems, while in some other cases, several cyber components have to be repaired first to restore the communications with important physical parts.

- *Interdependent critical infrastructures*. The interdependencies among different critical infrastructures make the resilience enhancement of power grids more complicated. For example, transportation networks (including road networks) and power networks are highly coupled, partly due to the increasing penetration of electric vehicles. In improving grid resilience, the power demands of transportation systems, the use of road networks to deliver flexibility resources, and the coordinated charging/discharging of electric vehicles, etc. have to be considered or dealt with. Other essential interdependencies, e.g. between natural gas networks and power grids, also need to be studied for resilience objectives so that the involved flexibility in different stages and areas can be fully coordinated and co-optimized.

1.5 Focus of This Book

Researchers and engineers in the electric power industry around the world have been conducting diversified studies or practices to attain the aforementioned components of power grid resilience, e.g. applying information and communications technologies in power grid controls. Among many worth-investigating topics on power grid resilience against disastrous events, this book concentrates on three critical issues, i.e. preparedness prior to disasters, response as disasters unfold, and recovery after disasters.

Specifically, this book summarizes the authors' selected research accomplishments related to the challenges or issues mentioned in the above sections, so as to provide applicable methods and some insights for the development of resilient power grids.

The main objectives of the research involved in this book include the following:

- *Preparedness prior to a natural disaster*.
  - Establish an optimal and coordinated preventive maintenance strategy that considers harsh external conditions (Chapter 2).
  - Construct a two-stage dispatch framework for the preallocation and real-time allocation of emergency resources to improve grid survivability (Chapter 3).
  - Develop a new approach to distribution grid automation that allocates remote-controlled switches empowering prompt restoration (Chapter 4).

- *Response as a natural disaster unfolds.*
  - Provide a sequential steady-state security region-based method to describe grid operability impacted by sequential extreme events (Chapter 5).
  - Propose a proactive operation strategy to enhance grid resilience during an unfolding extreme event considering uncertain sequential transitions of grid states (Chapter 6).
  - Develop a Markov decision process-based approach for distribution grids' real-time response throughout an unfolding event (Chapter 7).
- *Recovery after a natural disaster*.
  - Establish a new formulation of distribution grid topology constraints enabling restoration methods that use dynamically formed microgrids with flexible and adaptive boundaries (Chapter 8).
  - Construct a resilient routing and scheduling method for mobile power sources used in microgrids to enhance both survivability and recovery (Chapter 9).
  - Propose a novel co-optimization approach that coordinates the utilization of various flexibility resources in postdisaster recovery logistics (Chapter 10).

1.6 Summary

This chapter provides a general overview of resilience research and practice in power grids that have been endangered by natural disasters. The resilience concept is clarified based upon its definitions, importance and benefits, and challenges. Then, some relevant studies on grid resilience enhancement against disasters are discussed, divided by stages of resilience objectives, i.e. preparedness prior to disasters, response as disasters unfold, and recovery after disasters. Additionally, selected coordination and co-optimization issues in enhancing grid resilience are discussed. Last but not least, the focus of this work is clarified.

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