Front. Eng. Manag. 2017, 4(3): 271–282
DOI 10.15302/J-FEM-2017030

REVIEW ARTICLE

Gang HUANG, Jianhui WANG, Chen CHEN, Chuangxin GUO, Bingquan ZHU

System resilience enhancement: Smart grid and beyond

Abstract Boosting the resilience of power systems is a core requirement of smart grids. In fact, resilience enhancement is crucial to all critical infrastructure systems. In this study, we review the current research on system resilience enhancement within and beyond smart grids. In addition, we elaborate on resilience definition and resilience quantification and discuss several challenges and opportunities for system resilience enhancement. This study aims to deepen our understanding of the concept of resilience and develop a wide perspective on enhancing the system resilience for critical infrastructures.

Keywords critical infrastructure, cyber-physical systems, energy systems, resilience, smart grid

1 Introduction

Traditionally, our society depends on the provision of reliable and efficient services provided by critical infrastructures, such as power grids, gas networks, and oil fields. Adapting to the 21st century, our critical infrastructure is facing rapidly growing uncertainty and therefore becoming vulnerable to not only natural disasters (e.g., hurricanes and flooding) but also man-made disruptions (e.g., human errors and terrorist attacks). As a result, the concept of resilience is recently introduced into critical infrastructure systems (Tierney and Bruneau, 2007; National Infrastructure Advisory Council, 2009; White House, 2013; Panteli and Mancarella, 2015a; Wang et al., 2016a; Huang et al., 2017).

The report “Critical Infrastructure Resilience: Final Report and Recommendations,” (National Infrastructure Advisory Council, 2009), released by the National Infrastructure Advisory Council (NIAC) in September 2009, has recognized the significance of resilience for critical infrastructures. On February 12, 2013, the White House has released the Presidential Policy Directive 21—Critical Infrastructure Security and Resilience (White House, 2013) in response to the recommendations from NIAC. Thereafter, resilience has created an active field of research led by the government and attracted much attention in the academia and industry. In the 2015 Asia-Pacific Economic Cooperation agenda, resilience has also become a key theme (Asia-Pacific Economic Cooperation, 2015). The term “resilience” has also been repeated over 240 times in the proceedings of the Third United Nations World Conference on Disaster Risk Reduction (U.N. Office for Disaster Risk Reduction, 2015). As officially announced by the World Energy Council in World Energy Council (2015), enhancing the resilience of critical infrastructures is not an option but a must to date.

This study explores how to enhance the system resilience for critical infrastructures to satisfy the compelling urge to provide resilient services against disaster scenarios. Specifically, power grids, energy systems, and cyber-physical systems will be covered in this study. Power grids are regarded as one of the most vital critical infrastructures, energy systems consist of power grids and other physical systems (e.g., gas and oil systems), and cyber-physical systems are integration of cyber and physical systems. The relationships among power grids, energy systems, and cyber-physical systems are illustrated in Fig. 1. We will also elaborate on resilience definition and

Received April 29, 2017; accepted August 15, 2017

Gang HUANG (✉), Chuangxin GUO
College of Electrical Engineering, Zhejiang University, Hangzhou 310027, China
E-mail: huanggang@zju.edu.cn

Jianhui WANG
Department of Electrical Engineering, Southern Methodist University, Dallas, TX 75205, USA; Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA

Chen CHEN
Energy Systems Division, Argonne National Laboratory, Argonne, IL 60439, USA

Bingquan ZHU
State Grid Zhejiang Electric Power Company, Hangzhou 310027, China

resilience quantification. Several challenges and opportunities for system resilience enhancement will be provided on the basis of our observations. Through this study, we aim to engender a deep understanding of the concept of resilience and how to enhance it for different critical infrastructure systems.

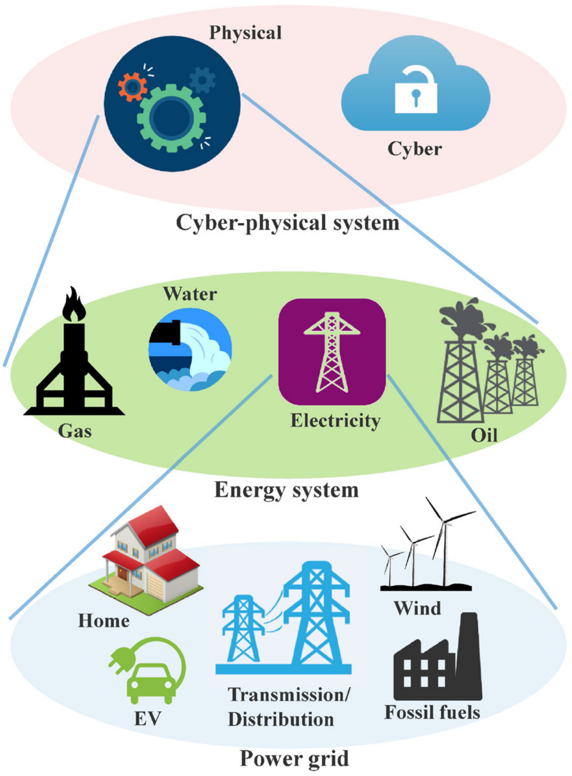

Fig. 1 Illustration of the relationships among power grids, energy systems, and cyber-physical systems

The remainder of the paper is organized as follows. Section 2 reviews several resilience definitions and resilience metrics. Section 3 introduces the current research on power grid resilience enhancement, and Section 4 extends the review to critical infrastructure systems beyond smart grids. Section 5 provides several challenges and opportunities, and Section 6 elaborates the concluding remarks.

2 System resilience

Prior to introducing the works on system resilience enhancement, the meaning of system resilience and its proper measurement method should be first determined. Thus, this section presents a literature survey of resilience definitions and resilience quantifications in existing studies.

2.1 Definition

The concept of resilience differs from that of reliability, as the latter has been more broadly investigated in the past and is more well established in the present than the former. Furthermore, the focus of reliability is on high-probability events, whereas the focus of resilience is on high-impact events. For example, in the context of power systems, a reliable system can withstand common disturbances (e.g., N-1 failure), but a resilient system must deal with large disturbances (e.g., flooding and storms). High-impact events are often less likely to happen; thus, the term “high-impact low-probability events” and the term “high-impact events” can be found to be interchangeably used in literature (e.g., Panteli and Mancarella, 2015b; Panteli et al., 2016; Panteli et al., 2017a).

Several resilience definitions can be found in considerable literature. A pioneer work is Holling (1973), which defined resilience as “the ability of a system to absorb changes of state variables, driving variables, and parameters, and still persist” for ecological systems. One of the pioneer works for critical infrastructure resilience is from the Multidisciplinary Center for Earthquake Engineering Research (MCEER). In their work (Bruneau et al., 2003), MCEER defined resilience as “the ability of social units to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future disasters.” NIAC defined resilience as “the ability to reduce the magnitude and/or duration of disruptive events” (National Infrastructure Advisory Council, 2009), while the U.S. Department of Homeland Security (DHS) defined resilience as “the ability to resist, absorb, recover from, or successfully adapt to adversity or a change in conditions” (U.S. Department of Homeland Security, 2009). Resilience was also defined as “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions” by the White House (White House, 2013). Recently, in the field of power systems, resilience was defined by Panteli and Mancarella (2015a) as “the ability to withstand extraordinary and high-impact low-probability events, rapidly recover from such disruptive events, and adapt its operation and structure to prevent or mitigate the impact of similar events in the future.” Then, Panteli et al. (2017a) extended this definition to “the ability of a system to anticipate and withstand external shocks, bounce back to its pre-shock state as quickly as possible, and adapt to be better prepared to future catastrophic events” for general critical infrastructures. Other resilience definitions are also available, such as “the system’s ability to resist different possible hazards, absorb the initial damage, and recover to normal operation” in Ouyang and Dueñas-Osorio (2012), Ouyang et al. (2012), Ouyang and Dueñas-Osorio (2014) and “the speed at which a system returns to equilibrium after a disturbance away from equilibrium" in D'Lima and Medda (2015). Over 70 definitions for resilience can be found in different disciplines in literature (Fisher, 2015).

As a synthesis of the available literature, all the definitions vary between two features, namely, adaptation and recovery (Fisher, 2015). In the current study, we define "adaptation" as the process of changing to make the system suitable for a new situation and "recovery" as the process of returning to a normal condition after a period of disturbance. On the basis of this observation, we define resilience as "the ability of a system to adapt to disaster scenarios and recover to pre-disaster states" (Huang et al., 2017). This definition is concise but reflects both features that all the different definitions share and is applicable to not only power grids but also systems in other disciplines. In addition, "disaster" in our resilience definition can mean natural disasters and man-made disruptions; "disaster" can represent a general disturbance that can cause high impact to a system.

2.2 Quantification

As a pioneer in investigating critical infrastructure resilience, MCEER proposed a general approach based on the characterization of system performance to measure the seismic resilience in Bruneau et al. (2003), where the resilience was measured by the size of the expected degradation in quality over the time to recovery. Thereafter, the "resilience triangle" was explicitly proposed by Tierney and Bruneau (2007) for the first time. This concept indicates two metrics for quantifying system resilience: One is infrastructure performance, which represents the loss of functionality from the damage; the other is recovery time, which represents the pattern of restoration over time. The hypotenuse of the resilience triangle can vary from linear function to sophisticated forms, such as exponential and trigonometric functions (Cimellaro et al., 2010).

Panteli et al. (2017a) extended the resilience triangle by proposing the "resilience trapezoid" to provide a complete picture of critical infrastructure resilience level during different phases of an event. The resilience trapezoid was quantified using a metric framework called "ΦΛΕΠ," where five metrics were defined: how low (Φ) and how fast (Λ) resilience drops when the disaster event hits a system, how long (Ε) it resides to the post-disaster degraded state, how fast (Π) it recovers to its pre-disaster state, and an area metric expressed as the integral of the trapezoid to support the assessment of overall impact. The resilience trapezoid can already be found in a few early works. For example, Ouyang and Dueñas-Osorio (2012), Ouyang et al. (2012), and Ouyang and Dueñas-Osorio (2014) introduced a time-dependent resilience metric based on a trapezoid, and this metric was qualified as the ratio of the area between real performance curve and time axis to the area between target performance curve and time axis. However, Panteli et al. (2017a) was the first to adequately and methodically model the trapezoid for system resilience.

Other resilience measurements can also be found in literature. For example, the Infrastructure Assurance Center at Argonne National Laboratory, in partnership with the Protective Security Coordination Division of the U.S. DHS, has developed the Resilience Measurement Index (RMI) to characterize the resilience of critical infrastructures (Petit et al., 2013). RMI was valued from 0 (low resilience) to 100 (high resilience), thereby providing resilience comparisons for critical infrastructures and guiding prioritization for improving resilience. Gathering a diverse group of experts from academia, industry, and government, the U.S. Department of Energy (DOE) has held a technical workshop with the theme "Resilience Metrics for Energy Transmission and Distribution Infrastructure" for the 2014 Quadrennial Energy Review (U.S. Department of Energy, 2014) to identify and explore issues important to resilience quantification. Ji et al. (2017) discussed fundamental challenges and advanced approaches for quantifying resilience, and resilience metrics for energy systems have been broadly reviewed by the RAND Corporation (Willis and Loa, 2015).

In our previous work (Huang et al., 2017), we minimized the total load shed to enhance power grid resilience because the system resilience was quantitatively measured by the total load served. The larger the served proportion of the total load demand, the smaller the shed proportion of the total load demand and the higher the resilience of the system. This quantification method utilizes the advantage of basic elements in a system and can explicitly reflect the system performance and the effectiveness of enhancement strategies (Bie et al., 2017). This method can also be easily extended to quantify the system resilience for other critical infrastructures, as these systems are all designed to meet a certain form of demand. In addition, the per-unit calculation can be leveraged to compensate for the scale effects of different systems. Then, we can provide resilience comparisons for systems in different scales.

3 Power grid resilience enhancement

The U.S. National Academy of Engineering has identified electrification as the most significant engineering achievement of the 20th century (Constable and Somerville, 2003). Moreover, electricity has already become the lifeblood of our modern society, and the power grid is widely regarded as one of the most vital critical infrastructure. To make the grid strong and smart against disasters, the concept of power grid resilience was introduced and has soon attracted much attention around the world. According to our previous work on power grid resilience (Huang et al., 2017), system resilience enhancement strategies can be categorized into resilience planning,

Fig. 2 Milestones of resilience enhancement strategies. The blue storm image indicates disaster scenarios

resilience response, and resilience restoration. The milestones of resilience enhancement strategies are depicted in Fig. 2. In the figure, these milestones are classified according to the field of application (i.e., planning or operation) and the property of resilience (i.e., adaptation or recovery). Herein, we will follow this classification in summarizing the state-of-the-art strategies of power grid resilience enhancement.

3.1 Resilience planning

With the concept of power system planning (Shahidehpour, 2014), resilience planning can be divided into long-term planning, mid-term planning, and short-term planning, comprising a time span between a year and a day. This concept underpins resilience response and resilience restoration, which we will later discuss in Sections 3.2 and 3.3, by identifying the infrastructure investments and allocation needed to achieve the expected resilience.

In terms of resilience planning, infrastructure hardening constitutes the primary approach. The most common hardening strategy is upgrading the poles, which can be implemented by upgrading aluminum structures to galvanized steel lattice or concrete for power grid transmission systems and upgrading wooden poles to concrete, steel, or a composite material for distribution systems (Executive Office of the President, 2013). Other common hardening strategies include undergrounding power lines and pole reinforcing (Yuan et al., 2016). Salman et al. (2015) proposed a framework considering failure of poles and power delivery, component importance measure, hurricane hazard analysis, and decay of poles to evaluate the effectiveness of targeted hardening strategies on power distribution systems subjected to hurricanes. Ma et al. (2017) derived an optimal hardening strategy for distribution networks by proposing a tri-level optimization model that considers the probabilistic failures of hardened components to protect the grid against extreme weather events.

The management of trees and other flora around overhead lines is known as vegetation management (Wanik et al., 2017), which is also a major strategy for resilience planning. Trees near distribution lines are usually managed by trimming, and other management activities include the application of tree-growth regulators, the application of herbicides, and tree-removal and replacement programs (Kuntz et al., 2002). The North American Electric Reliability Corporation has enforced the applicable transmission owners to follow the vegetation management standards (NERC, 2012). The standards aim to guide the transmission owners in managing vegetation located on transmission rights of way and minimizing encroachments from vegetation located adjacent to the rights of way, thereby preventing the risk of vegetation-related outages that can lead to cascading blackouts. Establishing a fixed-time interval schedule based on tree growth and weather studies is a traditional method for vegetation management (Dai and Christie, 1994). Kuntz et al. (2002) derived an optimal vegetation management scheduling for distribution systems by proposing a maintenance-scheduling algorithm that can determine when and where to perform vegetation management.

Another major strategy for resilience planning is resource allocation. Gao et al. (2017) investigated the pre-hurricane generation resource allocation problem, where a stochastic mixed-integer nonlinear program was formulated to obtain an optimal plan in distribution systems. Yuan et al. (2016) proposed a resilient distribution network planning problem to coordinate the power line hardening and distributed generation resource allocation with the objective of minimizing the storm damage. Xu et al. (2016) formulated the placement of remote-controlled switches as a weighted set cover problem. Whipple (2014) proposed a robust optimization model to allocate repair crews before storms to minimize the possible restoration time. Lei et al. (2016) proposed a scenario-based two-stage stochastic optimization model to utilize the truck-mounted mobile emergency generators prior to natural disasters. Other resource allocation problems related to resilience planning include adding additional transmission lines (Wagaman, 2016) to increase power flow capacity, allocating power electronic-based controllers (Blaabjerg et al., 2017) to provide improved power flow control, and leveraging energy storage devices (Wen et al., 2016) to support the resilience response or accelerate the resilience restoration.

3.2 Resilience response

Considerable prior work has focused on resilience planning; however, system operators must also consider options to enhance power grid resilience from the perspective of operation, because operational strategies as “smart” measures can provide more specific and therefore more cost-effective strategies than resilience planning (Huang et al., 2017; Panteli et al., 2017b). These operational strategies are collectively called “resilience response” (Huang et al., 2017). On the basis of the traditional classification of power system operating states (Dy Liacco, 1967), resilience response can be further divided into preventive and emergency responses, which correspond to the preventive and emergency states, respectively. In general, preventive response is composed of the actions available before disaster scenarios unfold, and emergency response comprises the actions taken in the aftermath of a disaster. They are distinguished from the resilience planning and resilience restoration, as preventive and emergency responses are in relatively short time scales.

Preventive response generally includes generator redispatch (Wang et al., 2017a; Huang et al., 2017), topology switching (Huang et al., 2017), and adjustment of other facilities in the system. Notably, power grids in preventive state are being operated to satisfy all the demands without violating any operating constraints (Dy Liacco, 1967); thus, load shedding or similar actions should be avoided in the preventive state. Preventive response solely is often inadequate to keep the generation-demand balance against disasters (Huang et al., 2017). Therefore, most of the existing works have focused on emergency response instead to enhance power grid resilience.

Once a disaster unfolds, emergency response should be taken as soon as possible to mitigate the loss. The primary emergency response strategy is system islanding (also known as intentional islanding or controlled islanding), which is a last resort to prevent cascading failures. Traditional approaches to determine islands include the slow coherency analysis (You et al., 2004) and ordered binary decision diagrams (Sun et al., 2003). However, these methods cannot form multiple islands simultaneously; thus, optimization techniques are highly investigated recently for this problem. For example, Fan et al. (2012) used the mixed-integer programming approach to form islands in a power grid considering load shedding and connectivity constraints. Then, they formulated another two-stage stochastic programming model (Golari et al., 2014) and two-stage mixed-integer stochastic programming model (Golari et al., 2016) by considering severe contingencies. Trodden et al. (2013) provided a mixed-integer linear programming approach for controlled islanding to determine which lines to cut, loads to shed, and generators to adjust or switch off. Thereafter, they included voltage and reactive power constraints in their work and proposed an extended mixed-integer linear programming model (Trodden et al., 2014).

Although resilience response is classified into preventive and emergency responses due to the unfolding of disasters, we recently verified that preventive and emergency responses can also be integrated to further enhance system resilience (Huang et al., 2017). Huang et al. (2017) proposed an integrated resilience response (IRR) framework (Fig. 3), which not only can link the situational awareness with resilience enhancement but also can provide effective and efficient responses in preventive and emergency states. The core of the IRR framework is a two-stage robust mixed-integer optimization (RoMIO) model, which can directly yield the optimal strategy for preventive response and support the decision making for emergency state with the emergency response module of the RoMIO model (i.e., the RoMIO-E model).

3.3 Resilience restoration

Resilience restoration, which aims to restore the power system as quickly as possible to serve loads and minimize loss (Wang et al., 2016a), is the last milestone of resilience enhancement strategies. Resilience restoration has been an area of active research for a long time (Coffrin and Van

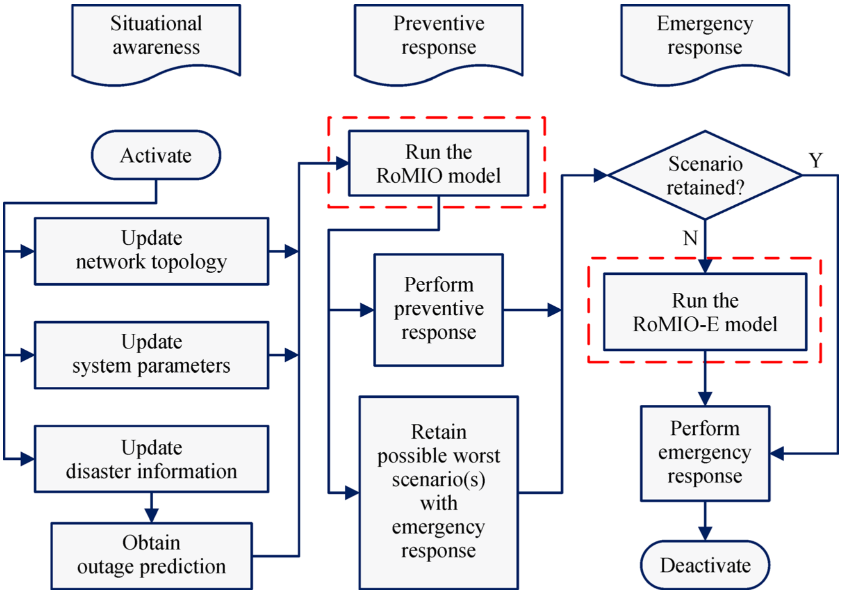

Fig. 3 IRR framework (adopted from Huang et al. (2017))

Hentenryck, 2015) and is traditionally divided into three stages, namely, restoration preparation, system restoration, and load restoration (Fink et al., 1995; Adibi and Fink, 2006; Qin, 2015).

After disasters unfold, the first step of restoration preparation is to conduct a complete assessment of the system, particularly the extent of the damage and the availability of post-disaster resources. On the basis of the system assessment, operators can provide customers with the estimated time of restoration and decide which restoration strategy to implement from the "bottom-up" strategy, "top-down" strategy, and hybrid strategy that combines the "bottom-up" and "top-down" strategies (PJM System Operations Division, 2016). In addition, after large disturbances (e.g., natural disasters), critical infrastructure may need to be repaired before system restoration or load restoration can be started. This repair scheduling problem has also attracted interest recently. For example, Van Hentenryck and Coffrin (2015) modeled this problem as a large-scale mixed nonlinear, nonconvex program and then proposed a two-stage approach to solve it. Furthermore, Tan et al. (2017) formulated the post-disaster repair scheduling problem in distribution networks as an integer linear programming using a multi-commodity flow model.

System restoration is the second stage of resilience restoration and aims to re-integrate the bulk power systems. Some loads can also be restored in this stage but only for the purpose of maintaining system stability (Adibi and Fink, 2006). Conventionally, operators must perform system restoration following the off-line guidelines. However, the details of an actual blackout cannot be easily predicted in the planning stage, thereby requiring on-line tools. To fill this gap, the Power Systems Engineering Research Center (PSERC) has completed a research project titled "Development and Evaluation of System Restoration Strategies from a Blackout" (Final Report of Power Systems Engineering Research Center (PSERC) Project S30, 2009). Through this project, four modules have been designed, including the generation capacity optimization module, transmission path search module, constraint checking module, and distribution system restoration module. Furthermore, Hou et al. (2011) proposed a concept called Generic Restoration Milestones (GRMs) by generalizing the industry practice of restoration. On the basis of the concept of GRMs, a decision-support tool entitled "System Restoration Navigator" has been developed with the support of the Electric Power Research Institute (EPRI) (Liu et al., 2012). EPRI also developed another tool called "Optimal Blackstart Capacity" to determine if blackstart resources are sufficient for system restoration (Qiu et al., 2016; Jiang et al., 2017).

After the system is restored with sufficient strength, load restoration becomes the major concern for operators. Load restoration has attracted a high level of interest, which is mainly attributed to the increasing penetration of distributed energy resources and the development of smart grid technologies. For example, Chen et al. (2016) formulated a mixed-integer linear programming model to maximize the critical loads to be picked up by utilizing remotely controlled switch devices and distributed generation. Gao et al. (2016) formulated the microgrid-assisted critical load restoration problem as a two-objective chance-constrained program under the uncertainties of renewable energy sources and load demand. Qin et al. (2015) formulated a mixed-integer nonlinear load restoration model to support the load restoration under reserve, frequency security, and steady-state constraints of power systems. During load restoration, cold load pickup (CLPU) is a specific phenomenon that has attracted certain attention. For example, Kumar et al. (2010) utilized the distributed generation to overcome the CLPU problem. Another issue in load restoration is that most distribution networks possess unbalanced configurations. Thus, Wang et al. (2016b) adopted a three-phase microgrid restoration model to capture the unbalanced characteristics. In addition, the majority of current works have depended on the assumption of radial topology, but future distribution systems can also be mesh networks (Heydt, 2010). Thus, further efforts are required to extend current approaches to optimally restore the mesh distribution networks.

4 Beyond the smart grid

As a core requirement of smart grids, the power grid resilience enhancement has been reviewed in Section 3. Herein, we will take a step forward and conduct a survey of system resilience enhancement studies for general critical infrastructures, including energy systems in Section 4.1 and cyber-physical systems in Section 4.2.

4.1 Energy systems

Energy systems form the backbone of our society and provide us electric power, natural gas, oil, and other forms of energy. However, the increasing interconnection of the energy sector, ranging from power systems to oil fields, makes the energy sector more complex than ever before. The exposure of energy systems to disasters is largely increasing (World Energy Council, 2015), thereby calling for the concept of energy system resilience, which refers to the capability of energy systems to adapt to disaster scenarios and recover to pre-disaster states.

Several works on energy system resilience planning are available. For example, Cimellaro et al. (2015) studied the resilience-based design of gas systems and showed that the functionality of medium-pressure gas distribution network is crucial for ensuring system resilience during post-earthquake stage while the best retrofit strategy should include emergency shutoff valves along the steel pipes. Pino et al. (2016) proposed a resilience metric for gas distribution networks to compare the effects of different pipeline upgrading plans. Shao et al. (2017) proposed an integrated electricity and natural gas transportation system planning algorithm by replacing segments of power grids with underground gas pipelines. Zlotnik et al. (2017) presented a framework for day-ahead scheduling of coupled electric power and natural gas infrastructure for different coordination scenarios and different operational methods of gas compressors. Wang et al. (2017b) proposed a tri-level optimization problem to harden the coupled electric power and natural gas systems against malicious attacks.

Relevant studies on energy system resilience response are as follows. Manshadi and Khodayar (2015) analyzed the resilience of multiple energy carrier microgrids exposed to disturbances in electric power and natural gas networks and formulated a bi-level optimization problem to ensure the resilient operation of coordinated electricity and natural gas infrastructure. Jaworsky et al. (2015) proposed a risk assessment methodology for coupled natural gas and electric power systems based on a probabilistic weather model, a detailed model of the interdependence between the gas and electricity infrastructure, and an optimization approach to identify the most dangerous weather and outage events; the efficiency of the proposed algorithm enables the use of arbitrarily sophisticated models of coupled infrastructure.

Ouyang and Wang (2015) investigated the restoration problem of interdependent power and gas networks, where a network-based framework was used to analyze the resilience contribution of five joint restoration strategies. Their results showed that, under limited restoration resources, the "random restoration" strategy produces the least resilience for both systems, the "independent restoration" strategy and the "power first and gas second" restoration strategy generate the largest resilience for the power system, and the "gas aimed" restoration strategy generates the largest resilience for the gas system. By quantifying the total resilience of both systems as evenly weighted sum of individual resilience, the "power and gas compromised" restoration strategy leads to the largest total resilience. Other issues during the resilience restoration process have also been studied. For example, Bragado (2016) investigated the problem of infrastructure system downtime estimation after earthquakes, where an empirical model was developed on the basis of damage data of earthquakes during the last hundred years. Marnay et al. (2015) studied Japan's energy system resilience after earthquakes and highlighted the significance of microgrids.

4.2 Cyber-physical systems

The digitization of critical infrastructure systems has brought in new methodologies and technologies for improved engineering management, and modern critical infrastructure systems therefore become cyber-physical systems. However, new vulnerabilities are also introduced. Recent incidents of attacks, such as the 2012 oil company attack in Saudi Arabia, the 2014 manufacturing attack in Germany, the 2015 power grid attack in Ukraine, and the 2016 power grid attack in Israel (World Energy Council, 2016), have highlighted the need for cyber-physical system resilience enhancement.

Buldyrev et al. (2010) developed a framework for resilience planning to understand the cascading failures in cyber-physical systems, and their findings emphasized the need to consider interdependent network properties in designing resilient systems. Qi et al. (2016) proposed an attack-resilient framework to protect the integrated distributed energy resources and critical power grid infrastructure from malicious cyber-attacks. Advanced sensors, such as phasor measurement units (PMUs), have been widely installed to support the resilience enhancement by system monitoring and observability. For example, Wen et al. (2013) proposed an optimization model that can fit the multistage installation scenario to decide the optimal placement of PMUs. Manousakis and Korres (2016) proposed a semidefinite programming-based model considering pre-existing conventional and synchronized phasor measurements and the limited channel capacity of PMUs, and Pal et al. (2017) presented an integer linear programming method considering realistic costs and trends in relaying technologies.

As an important problem of resilience response, attack detection has attracted much attention in cyber-physical systems. Pasqualetti et al. (2015) conducted a detailed survey on control-theoretic attack detection methods. Taha et al. (2016) utilized real-time measurements from PMUs to develop a robust dynamic state estimator against attacks. Given that PMUs can also be damaged in cyber-physical systems, Mousavian et al. (2015) proposed a mixed-integer linear programming model to prevent risk propagation and maintain the system observability, and Lin et al. (2016) formulated an integer linear programming model to exploit the features of dynamic and programmable configuration in a software-defined networking infrastructure to achieve resilience against cyber-attacks. Distributed computation has also been introduced into system operation decision making because it provides scalability, robustness, and privacy protection (Duan et al., 2016a). However, distributed computation can cause a large number of vulnerabilities to cyber-attacks (Duan et al., 2015). To tackle this issue, Duan et al. (2016b) proposed a resilient distributed DC optimal power flow algorithm against data integrity attacks using a neighborhood monitoring scheme, and Zeng et al. (2017) developed a neighborhood-watch-based distributed energy management algorithm with built-in resilient control design to maintain the system resilience.

Stefanov and Liu (2014) identified the problem of cyber-physical system restoration after blackouts for the first time. The problem is distinguished from the resilience restoration of traditional physical systems, as the control center and communication system may also be damaged due to cyber-attacks. Chen et al. (2016) designed a distributed multiagent coordination scheme to cope with the resilience challenge of communications after natural disasters, where global information discovery was achieved via only local communications. Other advanced communication technologies can also be of value for this challenge. Furthermore, resets can be used as an effective strategy to recover from a variety of software faults in cyber-physical systems, and a discussion of this issue can be found in Abad et al. (2016).

5 Challenges and opportunities

We have provided a literature review of system resilience enhancement in the sections above. Although some issues in this field have attracted much interest, many issues still require future research. The fast development of modern technologies opens up great opportunities for us, whereas the high complexity of these issues poses great challenges. On the basis of our observations, we discuss several challenges and opportunities regarding system resilience enhancement in this section.

5.1 Distributed energy resources

Distributed energy resources involve various technologies, including wind turbines, solar panels, energy storage, combined heat and power, electric vehicles, microgrids, and micro turbines. Traditionally, interconnection standards (e.g., the IEEE Standard 1547 (Basso, 2014)) require distributed energy resources to be disconnected against disasters. With the ever-increasing penetration of distributed energy resources, an urgent desire has come up to reconsider this issue. An example is the envisioning of utilizing distributed energy resources during the restoration process (Liu et al., 2014). Another example is the concept of exploiting distributed energy resources in resilience response to defend our systems.

Nevertheless, given that some distributed energy resources (e.g., wind and solar) are often volatile and difficult to accurately predict, dealing with the uncertainty can be a major issue in leveraging distributed energy resources for system resilience enhancement. Moreover, the difficulty in dealing with the uncertainty can be great as deep penetration of distributed energy resources is already underway. In addition, as revealed by a recent survey (Ginger, 2017), cost and financial constraints are cited by many utilities as an obstacle to hold them back from distributed energy resources. Thus, making distributed energy resources economical can be significant in promoting the utilization of these resources. Furthermore, we should be aware of the potential adverse impacts of distributed energy resources. For example, the introduction of distributed energy resources may lower the system inertia, bring the air pollution close to populated areas, and introduce certain negative environmental issues at the end of their lifespan.

5.2 Integrated approaches

As we have elaborated in Section 3.2, the IRR framework and the RoMIO model have been proposed for integrated resilience response (Huang et al., 2017). In addition, integrated solutions to resilience restoration problem have been recently investigated for distribution systems (Chen et al., 2017) and transmission systems (Qiu and Li, 2017). Integrated approaches intend to achieve holistic solutions to complex problems by integrating different kinds of strategies, and a timely motion to provide integrated approaches for system resilience enhancement exists.

However, accurately and efficiently formulating a problem as an integrated approach is a difficult task. The intrinsic nature of an integrated approach determines a high complexity of the formulated problem, and the high complexity may limit our ability to analyze and solve the problem. Thus, we should always pay attention to the problem formulation in enhancing the system resilience. Alternatively, high performance computing, mainly parallel computing and distributed computing, extends our ability to solve problems in a reasonable time. Nonetheless, efforts are required to transform original problems into specific forms to utilize the benefits of high performance computing.

5.3 Big data analytics

The ever-increasing deployment of advanced sensors and the ever-growing necessity in data collection have enabled big data analytics to provide another promising path for us to understand system resilience and enhance system resilience thereafter. An example can be found in Ji et al. (2016), where high-resolution and large-scale data on failure and recovery were used to study failure impact and recovery patterns. Machine learning (e.g., deep learning and reinforcement learning) as the cutting edge of artificial intelligence can be widely applied to analyze the collected data.

Nonetheless, a wide gap still exists between big data and big impact. Adequate data for considerable research are lacking. Thus, works in this field are few to date. To resolve this impediment, collaborative efforts from utilities and researchers are required. The scale of the flood of data challenges our ability to process large volumes of data in a short period of time, whereas the heterogeneity of big data presents further challenge on data integration. Data cleaning is necessary for big data analytics, as missing data or incorrect data cannot be ignored. We should also pay attention to the data privacy and data protection problem, which must be addressed to realize the promise of big data.

6 Concluding remarks

Resilience has recently attracted extensive attention, and system resilience enhancement has become an urgent task. This study mainly reviews the current research on system resilience enhancement for power grids, energy systems, and cyber-physical systems. We also elaborate on resilience definition and resilience quantification and discuss several challenges and opportunities for system resilience enhancement. The ultimate goal of system resilience enhancement leads to "smart systems."

Acknowledgements This work was supported by the Key Program of National Natural Science Foundation of China (Grant No. 51537010), the National Basic Research Program (973 Program) (Grant No. 2013CB228206), and the China Scholarship Council. J. Wang's work and C. Chen's work are supported by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability.

References

Abad F, Mancuso R, Bak S, Dantsker O, Caccamo M (2016). Reset-based recovery for real-time cyber-physical systems with temporal safety constraints. In: Proceedings of IEEE 21st International Conference on Emerging Technologies and Factory Automation. Berlin: IEEE, 1–8

Adibi M, Fink L (2006). Overcoming restoration challenges associated with major power system disturbances-restoration from cascading failures. IEEE Power & Energy Magazine, 4(5): 68–77

Asia-Pacific Economic Cooperation (2015). APEC 2015 themes and priorities. Retrieved from http://mddb.apec.org/Documents/2015/ECSG/ECSG1/15_ecsg1_012.pdf

Basso T (2014). IEEE 1547 and 2030 standards for distributed energy resources interconnection and interoperability with the electricity grid. Retrieved from http://www.nrel.gov/docs/fy15osti/63157.pdf

Bie Z, Lin Y, Li G, Li F (2017). Battling the extreme: A study on the power system resilience. Proceedings of the IEEE, 105(7): 1253–1266

Blaabjerg F, Yang Y, Yang D, Wang X (2017). Distributed power generation systems and protection. Proceedings of the IEEE, 105(7): 1311–1331

Bragado A (2016). Downtime estimation of lifelines after an earthquake. Thesis for the Master's Degree. Barcelona: Universitat Politècnica de Catalunya

Bruneau M, Chang S, Eguchi R, Lee G C, O'Rourke T D, Reinhorn A M, Shinozuka M, Tierney K, Wallace W A, von Winterfeldt D (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake Spectra, 19(4): 733–752

Buldyrev S V, Parshani R, Paul G, Stanley H E, Havlin S (2010). Catastrophic cascade of failures in interdependent networks. Nature, 464(7291): 1025–1028

Chen C, Wang J, Qiu F, Zhao D (2016). Resilient distribution system by microgrids formation after natural disasters. IEEE Transactions on Smart Grid, 7(2): 958–966

Chen C, Wang J, Ton D (2017). Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: An integrated solution. Proceedings of the IEEE, 105(7): 1267–1288

Cimellaro G, Reinhorn A, Bruneau M (2010). Framework for analytical quantification of disaster resilience. Engineering Structures, 32(11): 3639–3649

Cimellaro G, Villa O, Bruneau M (2015). Resilience-based design of natural gas distribution networks. Journal of Infrastructure Systems, 21(1): 05014005

Coffrin C, Van Hentenryck P (2015). Transmission system restoration with co-optimization of repairs, load pickups, and generation dispatch. International Journal of Electrical Power & Energy Systems, 72: 144–154

Constable G, Somerville B (2003). A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives. Washington, DC: The National Academies Press

Dai L, Christie R (1994). The optimal reliability-constrained line clearance scheduling problem. In: Proceedings of the Twenty-Sixth Annual North American Power Symposium. 1: 244–249

D'Lima M, Medda F (2015). A new measure of resilience: An application to the London underground. Transportation Research Part A, Policy and Practice, 81: 35–46

Duan J, Zeng W, Chow M (2015). Economic impact of data integrity attacks on distributed DC optimal power flow algorithm. In: Proceedings of North American Power Symposium, Charlotte: IEEE, 1–7

Duan J, Zeng W, Chow M (2016a). Attack detection and mitigation for resilient distributed DC optimal power flow in the IoT environment. In: Proceedings of IEEE 25th International Symposium on Industrial Electronics. Santa Clara: IEEE, 606–611

Duan J, Zeng W, Chow M (2016b). An attack-resilient distributed DC optimal power flow algorithm via neighborhood monitoring. In Proceedings of IEEE PES General Meeting. 1–5

Dy Liacco T E (1967). The adaptive reliability control system. IEEE Transactions on Power Apparatus and Systems, PAS-86(5): 517–531

Executive Office of the President (2013). Economic benefits of increasing electric grid resilience to weather outages. Retrieved from https://energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf

Fan N, Izraelevitz D, Pan F, Pardalos P M, Wang J (2012). A mixed integer programming approach for optimal power grid intentional islanding. Energy Systems, 3(1): 77–93

Final Report of Power Systems Engineering Research Center (PSERC) Project S30 (2009). Development and evaluation of system restoration strategies from a blackout. Retrieved from http://pserc.wisc.edu/documents/publications/reports/2009_reports/S-30_Final-Report_Sept-2009.pdf

Fink L, Liou K, Liu C (1995). From generic restoration actions to specific restoration strategies. IEEE Transactions on Power Systems, 10(2): 745–752

Fisher L (2015). Disaster responses: More than 70 ways to show resilience. Nature, 518(7537): 35

Gao H, Chen Y, Mei S, Huang S, Xu Y (2017). Resilience-oriented pre-hurricane resource allocation in distribution systems considering electric buses. Proceedings of the IEEE, 105(7): 1214–1233

Gao H, Chen Y, Xu Y, Liu C C (2016). Resilience-oriented critical load restoration using microgrids in distribution systems. IEEE Transactions on Smart Grid, 7(6): 2837–2848

Ginger J (2017). Distributed energy resources solution, challenge or both? Retrieved from http://www.elp.com/articles/powergrid international/print/volume-22/issue-3/features/distributed-energy-resources-solution-challenge-or-both.html

Golari M, Fan N, Wang J (2014). Two-stage stochastic optimal islanding operations under severe multiple contingencies in power grids. Electric Power Systems Research, 114: 68–77

Golari M, Fan N, Wang, J (2017). Large-scale stochastic power grid islanding operations by line switching and controlled load shedding. Energy Systems, 8(3): 601–621

Heydt G (2010). The next generation of power distribution systems. IEEE Transactions on Smart Grid, 1(3): 225–235

Huang G, Wang J, Chen C, Qi J, Guo C (2017). Integration of preventive and emergency responses for power grid resilience enhancement. IEEE Transactions on Power Systems, PP(99): 1–1

Holling C (1973). Resilience and stability of ecological systems. Annual Review of Ecology and Systematics, 4(1): 1–23

Hou Y, Liu C, Sun K, Zhang P, Liu S, Mizumura D (2011). Computation of milestones for decision support during system restoration. IEEE Transactions on Power Systems, 26(3): 1399–1409

Jaworsky C, Spataru C, Turitsyn K (2015). Vulnerability assessment for interdependent gas and electricity networks. In: Proceedings of 48th Hawaii International Conference on System Sciences. IEEE, 2766–2775

Ji C, Wei Y, Mei H, Calzada J, Carey M, Church S, Hayes T, Nugent B, Stella G, Wallace M, White J, Wilcox R (2016). Large-scale data analysis of power grid resilience across multiple US service regions. Nature Energy, 1(5): 16052

Ji C, Wei Y, Poor H (2017). Resilience of energy infrastructure and services: Modeling, data analytics and metrics. Proceedings of the IEEE, 105(7): 1354–1366

Jiang Y, Chen S, Liu C, Sun W, Luo X, Liu S, Bhatt N, Uppalapati S, Forcum D (2017). Blackstart capability planning for power system restoration. International Journal of Electrical Power & Energy Systems, 86: 127–137

Kumar V, Kumar H C R, Gupta I, Gupta H O (2010). DG integrated approach for service restoration under cold load pickup. IEEE Transactions on Power Delivery, 25(1): 398–406

Kuntz P, Christie R, Venkata S (2002). Optimal vegetation maintenance scheduling of overhead electric power distribution systems. IEEE Transactions on Power Delivery, 17(4): 1164–1169

Lei S, Wang J, Chen C, Hou Y (2016). Mobile emergency generator pre-positioning and real-time allocation for resilient response to natural disasters. IEEE Transactions on Smart Grid, PP(99): 1–1

Lin H, Chen C, Wang J, Kalbarczyk Z, Iyer R K (2016). Self-healing attack-resilient PMU network for power system operation. IEEE Transactions on Smart Grid, PP(99): 1–14

Liu S, Podmore R, Hou Y (2012). System restoration navigator: A decision support tool for system restoration. In: Proceedings of 2012 IEEE PES General Meeting. IEEE, 1–5

Liu S, Hou Y, Liu C, Podmore R (2014). The healing touch: Tools and challenges for smart grid restoration. IEEE Power & Energy Magazine, 12(1): 54–63

Ma S, Chen B, Wang Z (2017). Resilience enhancement strategy for distribution systems under extreme weather events. IEEE Transactions on Smart Grid, PP(99): 1440–1450

Manousakis N, Korres G (2016). Semidefinite programming for optimal placement of PMUs with channel limits considering pre-existing SCADA and PMU measurements. In: Proceedings of 2016 Power Systems Computation Conference. Genoa: IEEE, 1–7

Manshadi S, Khodayar M (2015). Resilient operation of multiple energy carrier microgrids. IEEE Transactions on Smart Grid, 6(5): 2283–2292

Marnay C, Aki H, Hirose K, Kwasinski A, Ogura S, Shinji T (2015). Japan's pivot to resilience: How two microgrids fared after the 2011 earthquake. IEEE Power & Energy Magazine, 13(3): 44–57

Mousavian S, Valenzuela J, Wang J (2015). A probabilistic risk mitigation model for cyber-attacks to PMU networks. IEEE Transactions on Power Systems, 30(1): 156–165

National Infrastructure Advisory Council (2009). Critical infrastructure resilience: Final report and recommendations. Retrieved from https://www.dhs.gov/publication/niac-critical-infrastructure-resilience-final-report

NERC (2012). FAC-003-3-transmission vegetation management. Retrieved from http://www.nerc.com/files/FAC-003-3.pdf

Ouyang M, Dueñas-Osorio L (2012). Time-dependent resilience assessment and improvement of urban infrastructure systems. Chaos (Woodbury, N.Y.), 22(3): 033122

Ouyang M, Dueñas-Osorio L (2014). Multi-dimensional hurricane resilience assessment of electric power systems. Structural Safety, 48: 15–24

Ouyang M, Dueñas-Osorio L, Min X (2012). A three-stage resilience analysis framework for urban infrastructure systems. Structural Safety, 36–37: 23–31

Ouyang M, Wang Z (2015). Resilience assessment of interdependent infrastructure systems: With a focus on joint restoration modeling and analysis. Reliability Engineering & System Safety, 141: 74–82

Pal A, Vullikanti A, Ravi S (2017). A PMU placement scheme considering realistic costs and modern trends in relaying. IEEE Transactions on Power Systems, 32(1): 552–561

Panteli M, Mancarella P (2015a). Influence of extreme weather and climate change on the resilience of power systems: Impacts and possible mitigation strategies. Electric Power Systems Research, 127: 259–270

Panteli M, Mancarella P (2015b). The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience. IEEE Power & Energy Magazine, 13(3): 58–66

Panteli M, Mancarella P, Trakas D, Kyriakides E, Hatziargyriou N (2017a). Metrics and quantification of operational and infrastructure resilience in power systems. IEEE Transactions on Power Systems, PP(99): 1–10

Panteli M, Trakas D, Mancarella P, Kyriakides E, Hatziargyriou N (2016). Boosting the power grid resilience to extreme weather events using defensive islanding. IEEE Transactions on Smart Grid, PP(99): 1–10

Panteli M, Trakas D, Mancarella P, Hatziargyriou N D (2017b). Power systems resilience assessment: Hardening and smart operational enhancement strategies. Proceedings of the IEEE, 105(7): 1202–1213

Pasqualetti F, Dorfler F, Bullo F (2015). Control-theoretic methods for cyberphysical security: Geometric principles for optimal cross-layer resilient control systems. IEEE Control Systems, 35(1): 110–127

Petit F, Bassett G, Black R, Buehring W A, Collins M J, Dickinson D C, Fisher R E, Haffenden R A, Huttenga A A, Klett M S, Phillips J A, Thomas M, Veselka S N, Wallace K E, Whitfield R G, Peerenboom J P (2013). Resilience measurement index: An indicator of critical infrastructure resilience. Retrieved from http://mddb.apec.org/Documents/2015/ECSG/ECSG1/15_ecsg1_012.pdf

Pino W, Worm D, van der Linden R, Kooij R (2016). The reliability of a gas distribution network: A case study. In: Proceedings of International Conference on System Reliability and Science. Paris: IEEE, 122–129

PJM System Operations Division (2016). PJM manual 36: System restoration. Retrieved from http://www.pjm.com/~/media/documents/manuals/m36.ashx

Qi J, Hahn A, Lu X, Wang J, Liu C (2016). Cybersecurity for distributed energy resources and smart inverters. IET Cyber-Physical Systems : Theory & Applications, 1(1): 28–39

Qiu F, Li P (2017). An integrated approach for power system restoration planning. Proceedings of the IEEE, 105(7): 1234–1252

Qiu F, Wang J, Chen C, Tong J (2016). Optimal black start resource allocation. IEEE Transactions on Power Systems, 31(3): 2493–2494

Qin Z (2015). Construction of generic and adaptive restoration strategies. Dissertation for the Doctoral Degree. Hongkong: The University of Hong Kong

Qin Z, Hou Y, Liu C, Liu S, Hou Y (2015). Coordinating generation and load pickup during load restoration with discrete load increments and reserve constraints. IET Generation, Transmission & Distribution, 9 (15): 2437–2446

Salman A, Li Y, Stewart M (2015). Evaluating system reliability and targeted hardening strategies of power distribution systems subjected to hurricanes. Reliability Engineering & System Safety, 144: 319–333

Shahidehpour M (2014). Introduction to power system planning. Retrieved from https://www.coursehero.com/file/8773363/1-Introduction-to-Power-System-Planning/

Shao C, Shahidehpour M, Wang X, Wang X, Wang B (2017). Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience. IEEE Transactions on Power Systems, PP(99): 1–11

Stefanov A, Liu C (2014). Cyber-physical system security and impact analysis. IFAC Proceedings Volumes, 47(3): 11238–11243

Sun K, Zheng D, Lu Q (2003). Splitting strategies for islanding operation of large-scale power systems using OBDD-based methods. IEEE Transactions on Power Systems, 18(2): 912–923

Taha A, Qi J, Wang J, Panchal J H (2016). Risk mitigation for dynamic state estimation against cyber attacks and unknown inputs. IEEE Transactions on Smart Grid, PP(99): 1–14

Tan Y, Qiu F, Das A K, Kirschen D S, Arabshahi P, Wang J (2017). Scheduling post-disaster repairs in electricity distribution networks

Tierney K, Bruneau M (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. TR News, 250

Trodden P, Bukhsh W, Grothey A, McKinnon K I M (2013). MILP formulation for controlled islanding of power networks. International Journal of Electrical Power & Energy Systems, 45(1): 501–508

Trodden P, Bukhsh W, Grothey A, McKinnon K I M (2014). Optimization-based islanding of power networks using piecewise linear AC power flow. IEEE Transactions on Power Systems, 29(3): 1212–1220

U.N. Office for Disaster Risk Reduction (2015). Proceedings of the third UN world conference on disaster risk reduction. Retrieved from http://www.preventionweb.net/files/45069_proceedingsthirdunitednationsworldc.pdf

U.S. Department of Energy (2014). Technical workshop: Resilience metrics for energy transmission and distribution infrastructure. Retrieved from https://energy.gov/epsa/downloads/technical-workshop-resilience-metrics-energy-transmission-and-distribution

U.S. Department of Homeland Security (2009). National infrastructure protection plan. Retrieved from https://www.dhs.gov/xlibrary/assets/NIPP_Plan.pdf

Van Hentenryck P, Coffrin C (2015). Transmission system repair and restoration. Mathematical Programming, 151(1): 347–373

Wagaman A (2016). PPL nearing completion of backup transmission line in Emmaus, upper Milford. Retrieved from http://www.mcall.com/news/local/eastpenn/mc-emmaus-new-ppl-transmission-line-20160119-story.html.

Wanik D, Parent J, Anagnostou E, Hartman B M (2017). Using vegetation management and LiDAR-derived tree height data to improve outage predictions for electric utilities. Electric Power Systems Research, 146: 236–245

Wang C, Hou Y, Qiu F, Lei S, Liu K (2017a). Resilience enhancement with sequentially proactive operation strategies. IEEE Transactions on Power Systems, 32(4): 2847–2857

Wang C, Wei W, Wang J, Liu F, Correa-Posada C M, Mei S (2017b). Robust defense strategy for gas-electric systems against malicious attacks. IEEE Transactions on Power Systems, 32(4): 2953–2965

Wang Y, Chen C, Wang J, Baldick R (2016a). Research on resilience of power systems under natural disasters—A review. IEEE Transactions on Power Systems, 31(2): 1604–1613

Wang Z, Wang J, Chen C (2016b). A three-phase microgrid restoration model considering unbalanced operation of distributed generation. IEEE Transactions on Smart Grid, PP(99): 1–11

Wen M, Xu J, Li V (2013). Optimal multistage PMU placement for wide-area monitoring. IEEE Transactions on Power Systems, 28(4): 4134–4143

Wen Y, Li W, Huang G, Liu X (2016). Frequency dynamics constrained unit commitment with battery energy storage. IEEE Transactions on Power Systems, 31(6): 5115–5125

Whipple S (2014). Predictive Storm Damage Modeling and Optimizing Crew Response to Improve Storm Response Operations. Thesis for the Master's Degree. Boston: Massachusetts Institute of Technology

White House (2013). Presidential policy directive-critical infrastructure security and resilience. Retrieved from https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

Willis H, Loa K (2015). Measuring the resilience of energy distribution systems. Retrieved from http://www.rand.org/content/dam/rand/pubs/research_reports/RR800/RR883/RAND_RR883.pdf

World Energy Council (2015). The road to resilience: Managing and financing extreme weather risks. Retrieved from https://www.worldenergy.org/wp-content/uploads/2015/09/The-Road-to-Resilience-Managing-and-Financing-Extreme-Weather-Risk.pdf

World Energy Council (2016). The road to resilience: Managing cyber risks. Retrieved from https://www.worldenergy.org/wp-content/

uploads/2016/09/20160926_Resilience_Cyber_Full_Report_WEB-1.pdf

Xu Y, Liu C, Schneider K, Ton D T (2016). Placement of remotecontrolled switches to enhance distribution system restoration capability. IEEE Transactions on Power Systems, 31(2): 1139–1150

You H, Vittal V, Wang X (2004). Slow coherency-based islanding. IEEE Transactions on Power Systems, 19(1): 483–491

Yuan W, Wang J, Qiu F, Chen C, Kang C, Zeng B (2016). Robust optimization-based resilient distribution network planning against natural disasters. IEEE Transactions on Smart Grid, 7(6): 2817–2816

Zeng W, Zhang Y, Chow M (2017). Resilient distributed energy management subject to unexpected misbehaving generation units. IEEE Transactions on Industrial Informatics, 13(1): 208–216

Zlotnik A, Roald L, Backhaus S, Chertkov M, Andersson G (2017). Coordinated scheduling for interdependent electric power and natural gas infrastructures. IEEE Transactions on Power Systems, 32(1): 600–610