INVITED PAPER

Battling the Extreme: A Study on the Power System Resilience

This paper presents a load restoration framework based on distribution automation technologies.

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ABSTRACT | The electricity infrastructure is a critical lifeline system and of utmost importance to our daily lives. Power system resilience characterizes the ability to resist, adapt to, and timely recover from disruptions. The resilient power system is intended to cope with low probability, high risk extreme events including extreme natural disasters and man-made attacks. With an increasing awareness of such threats, the resilience of power systems has become a top priority for many countries. Facing the pressing urgency for resilience studies, the objective of this paper is to investigate the resilience of power systems. It summarizes practices taken by governments, utilities, and researchers to increase power system resilience. Based on a thorough review on the existing metrics system and evaluation methodologies, we present the concept, metrics, and a quantitative framework for power system resilience evaluation. Then, system hardening strategies and smart grid technologies as means to increase system resilience are discussed, with an emphasis on the new technologies such as topology reconfiguration, microgrids, and distribution automation; to illustrate how to increase system resilience against extreme events, we propose a load restoration framework based on smart distribution technology. The proposed method is applied on two test systems to validify its effectiveness. In the end, challenges to the power system resilience are discussed, including extreme event modeling, practical barriers, interdependence with other critical infrastructures, etc.

KEYWORDS | Critical infrastructure; extreme event; natural disaster; power system; resilience

I. INTRODUCTION

The power system is the foundation for a modern society, and its safe and efficient operation is the prerequisite for our social and economic life. Even though component failures often occur due to weather or its stochastic nature, power systems are designed to resist stochastic component outage under the N-1 security principle. However, recently many natural disasters and man-made attacks have brought unprecedented challenges to the power systems, causing sustained power outages, which highlights the situation that the power system is ill-prepared for extreme events of large scale and severity level, e.g., in 2008, a snow storm hit Southern China and caused over 129 line faults, which led to power loss for 14.66 million households; in the Great East Japan Earthquake in 2011, over 4 million households suffered from power outage for over seven to nine days; in 2012, Hurricane Sandy landed on the east coast of the United States and caused power outage for millions of people; in 2016, a tornado hit Jiangsu Province, China, which tripped over two 500-kV transmission lines, four 220-kV transmission lines, eight 110-kV transmission lines, and caused power outage for 135 000 households. Worse still, it is anticipated that such disasters would occur in increasing rates because of climate change and the aging energy infrastructure [1].

At the same time, threats for the power system also include human errors and man-made attacks (see Fig. 1) [2]. In the age of smart grid, the communication, computing, and control components embedded in the power system render the system more sophisticated and vulnerable. The power system is influenced by the intrinsic stochasticity and external disruptions, and its operation is interdependent on the energy flow, capital flow, and information flow. As a large-scale cyber–physical system, power system can be vulnerable to targeted

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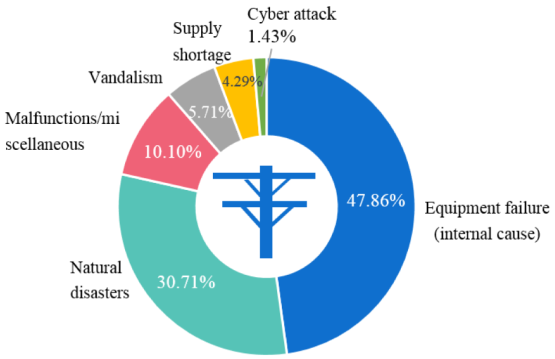


Fig. 1. ***Power outage causes for 140 worldwide outage data from 1965 to 2012.***

attacks. For example, 17 electrical transformers were attacked by gunfire in Metcalf California in 2013, showing that the power system is an easy target for terrorist attacks. Therefore, facing the increasing threats and complexity of the system, building resilience into our energy infrastructure is a challenging undertake.

While higher disaster-resistant construction standards should be adopted, a comprehensive upgrade of the whole system is too costly to be possible. As an alternative, the concept of resilient power system is put forward as a solution to deal with the low-probability, high-loss extreme events. As indicated by previous extreme natural disasters, utilities have realized that it is not possible to prevent all events at all time. So when load shedding is inevitable, it is more cost effective to allow the system to function in a degraded manner for a short period of time, just to return to the normal operation level fast and efficiently.

Under this circumstance, to achieve resiliency of the power system has become a top priority for many countries in recent years. Instead of waiting passively for the disaster to pass, there are numerous measures before, during, and after the event that utilities can actively adopt to guarantee supply to the critical loads despite failures in other areas. To understand power system resilience, this paper reviews the existing works on definition, evaluation, and improvement of resilience with a focus on the power system. We provide a general framework for evaluating power system resilience, presenting various specific resilience metrics and evaluation methodologies. In addition, we discuss innovative technologies that are put into places that allow the power system to react faster and restore more efficiently. A resilience improvement strategy based on the current technology in the distribution system is proposed and validated in test systems. Finally, new challenges for the power system resilience are outlined and discussed.

II. UNDERSTANDING RESILIENCE FOR POWER SYSTEM

A. Exploring the Essence of Resilience

In this section, resilience definition is discussed. Resilience was first introduced by Holling [3] in 1972 as a concept in ecological system, which referred to "a measure of the persistence of systems and of their ability to absorb change and disturbances and still maintain the same relationships between populations or state variables" [3]. Over the past few decades, resilience was widely adopted in research in the environment science, economy, psychology, material science, disaster engineering, etc. For the energy infrastructure, the power system in particular, many definitions of similar essence have been put forward, with a focus on the ability to deal with disruptions. The U.S. Presidential Policy Directives-21(PPD-21) defines resilience as "the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions" [4]. According to the U.K. Cabinet Office, resilience is the ability to "anticipate, absorb, adapt to and/or rapidly recover from a disruptive event" [5]. The Multidisciplinary Center for Earthquake Engineering Research (MCEER) introduced a general framework to define seismic resilience and characteristics of resilience including robustness, redundancy, resourcefulness, and rapidity, in technical, organizational, social, and economic dimensions [6]. Resilience is defined by the United Nations Office for Disaster Reduction (UNISDR) as [7]: "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions."

Though consensus on resilience definition is lacking, the essence of resilience definitions is generally the same, that is, it is an overarching concept that encompasses the system performance before and after disastrous events. Resilience therefore can be defined as "the ability of an entity to anticipate, resist, absorb, respond to, adapt to and recover from a disturbance" [8], as illustrated in Fig. 2. As indicated by the bold line, a resilient system is expected to resist the disruption better than the traditional system (indicated by the red dashed line), e.g., from t_0 to t_1, advanced weather forecast and decision support system can be employed for the anticipation and preparation for disasters; from t_1 to t_2, the system can better resist the disasters through system hardening; from t_1 to t_2, response and adaption can be realized through efficient resource dispatching methods, and finally more advanced restoration strategies such as microgrid islanding will be employed in a timely manner to restore the system to near-normal performance level.

In recent years, resilience has been increasingly recognized as a new design and operation goal for the critical infrastructures. For researchers and utility grids, it is becoming clear that it is not possible to resist all events at all time, and strategies beyond traditional reliability study are needed to keep the lights on under extreme events [9]. The focus of resilience is different from reliability, vulnerability, etc., in that extreme events are rare, can cause multiple instantaneous component failures, affect a large number of customers, and require relatively complex restoration strategies. In contrast, widely accepted reliability metrics, including the System Average Interruption Duration Index (SAIDI), the System Average Interruption Frequency Index (SAIFI), and the Customer Average Interruption Duration Index (CAIDI), often exclude

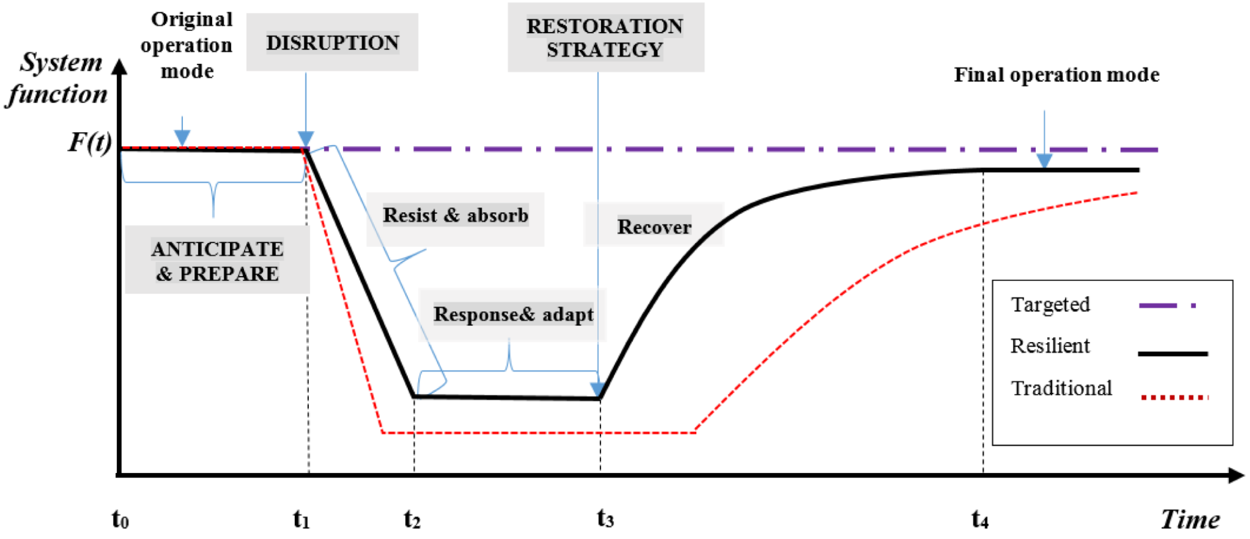


Fig. 2. ***Illustrative process of a resilient power system through disruption.***

major outages caused by unexpected events [10]. As a result, by existing reliability metrics, a highly reliable power system is not necessarily resilient. The core of resilience is not purely aiming to resist all possible disaster scenarios, but to have fast efficient restoration measures as well.

B. The Increasing Awareness of Resilience in the Power System

While recognizing the importance of resilience, research priorities have been put to different aspects of the system. In 2009, the U.S. Department of Energy (DOE) claimed that resilience should be a characteristic of the smart grid [11]. Two U.S. Presidential Policy Directives, PPD-8 and PPD-21, specifically addressed the national preparedness for critical infrastructure, and emphasized that the power system is uniquely critical due to its enabling functions it provides across all other critical infrastructures. The aging infrastructure is considered as the main cause for the power outages in the United States [12]. Therefore, the investment in the United States mainly goes to grid modernization efforts, e.g., under the American Recovery and Reinvestment Act of 2009 by DOE, the investment in grid modernization totaled about $9.5 billion. For the U.K. Government, while acknowledging the necessity of resilience in the power system in the face of narrowing generation margin and extreme natural disasters, government bodies have taken measures to ensure resilience planning and operation in the long term [13]. This is also supported by research efforts, e.g., the Resilience Electricity Networks for Great Britain (RESNET) project is dedicated to developing simulation tools to analyze power system in extreme weather conditions. Recovering from the earthquake and tsunami at Tokushima, the National Resilience Program of Japan totaled $210 billion investment in 2013, focusing on the overall resilience of critical energy, water, transport, and other critical infrastructures [14].

On the other hand, to keep the lights on, China has the largest installed power generation capacity in the world, the largest hydro installation, and renewable energy installation, as the most significant challenge in the power system in China is still the growing power demand [15]. To overcome outage caused by supply deficiency, extreme-high-voltage (EHV) and ultrahigh-voltage (UHV) transmission systems are being constructed, which can transmit power from the energy-rich Western China to the densely populated Eastern China. Power system resilience efforts have been led by the Chinese power utility companies in the transmission sector after the major snowstorm in South China that caused power outage for 14.66 million households in 2008. The Power System Collapse Prevention System [16] was installed, in particular, the so-called "Three Defense Lines" are employed, including economic operation &control, emergency control, and grid splitting control. Being aware that the majority of outages have roots in the distribution system, the Chinese National Energy Administration allocated 20 trillion CNY for the distribution renovation during 2015–2020, to increase reliability, power quality, and resilience to disruptions.

Resilience is further promoted to the community/society level. It is believed by governments, scholars, and research institutes that achieving resilience in the community and infrastructures can lead to massive savings through risk reduction and expeditious recovery [17]. Critical infrastructure is an integrated component to the community/society, and achieving resilience in the power system has benefits that transcend the system itself.

III. POWER SYSTEM RESILIENCE EVALUATION

In this section, works on power system resilience evaluation are selected and reviewed. The application of resilient planning and operation is facilitated by the proper evaluation of resilience and associated metrics. There has been a large

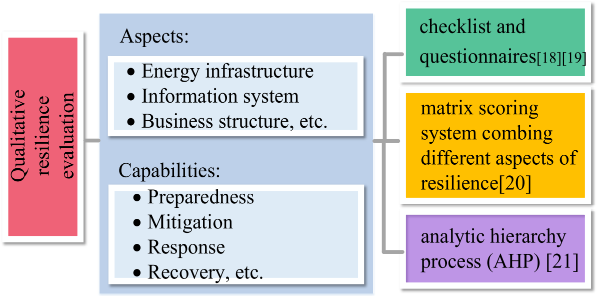


Fig. 3. ***Qualitative resilience evaluation methods.***

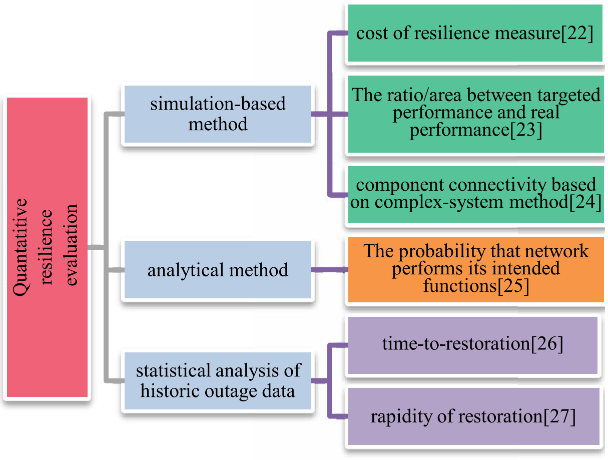


Fig. 4. ***Quantitative resilience evaluation methods.***

body of literature on this topic of resilience definition and evaluation. The existing works on the resilience evaluation usually fall into two groups: qualitative methods and quantitative methods.

A. Qualitative Power System Resilience Evaluation

The main qualitative power system resilience evaluation methods have been listed in Fig. 3. In the qualitative evaluation, the different aspects and different resilience capabilities can be considered simultaneously. The aspects considered in the qualitative evaluation usually include the power system and other interdependent systems, such as information system, fuel supply chain, etc. Capabilities include preparedness, mitigation, response, and recovery, e.g., the existence of emergency plan, personnel training, repair crew availability, etc. The evaluation methods are diverse, for example, Carlson *et al.* [18] and McManus *et al.* [19] provide frameworks for system-level and regional-level resilience overview using investigation, questionnaires, and individual ratings to address personal, business, governmental, and infrastructure aspects of resilience; a scoring matrix is formulated in [20] to evaluate the system function from different perspective; analytic methods such as analytic hierarchy process (AHP) can be conveniently employed to turn subjective opinions into comparable quantities, which is easy to use in decision making [21]. These qualitative frameworks can serve as a guidance for long-term energy policy making, as they provide a generally thorough picture of the system.

B. Quantitative Power System Resilience Evaluation

Quantitative methods, on the other hand, are often based on the quantification of system performances. Quantitative metrics are useful when evaluating the effectiveness of certain resilience measures or comparing the level of resilience of different systems. According to the review, resilience is quantitatively reflected in the reduced magnitude and duration of deviation from the targeted performance. Quantitative resilience metrics should be performance related and event specific, can reflect uncertainty, and should be useful for decision making, etc [22]. Some most common methods and metrics to evaluate power system resilience are summarized in Fig. 4.

From Fig. 4 it can be seen that the quantitative resilience evaluation mainly falls into three categories: the simulation-based method, the analytic method, and the statistical analysis.

Among them, the simulation-based method is most widely used because it can be easily combined with disaster scenarios and the disaster consequence can be readily calculated, e.g., in [22] and [23], the power flow analysis is adopted, and in [24], the complex network model is adopted. The analytical method, on the other hand, exploits the probability of system failure in a certain situation, e.g., Whitson and Ramirez-Marquez [25] define resilience as the probability that the network performs its intended function in the presence of external causes of component failure. For systems that have accumulated past natural disaster event data, historic outage and restoration records can be used for data analysis, as is done in [26] and [27].

Concerning the resilience metrics, restoration cost, restoration probability, or time to restoration have been used to describe resilience. The resilience triangle model proposed by MCEER in [23] was also widely used to quantify the resilience in earthquakes. The meaning of the resilience triangle is to evaluate the difference between the expected system performance and the real system performance, and transform the divergence into different forms. Based on Fig. 2, the real and targeted functions of the infrastructure at time t are denoted with $F(t)$ and $F_0(t)$. Let R denote resilience, and its value is

$$R = \int_{t_1}^{t_4} [F_0(t) - F(t)]dt. \qquad (1)$$

Another branch of research synthesizes composite resilience value that combines the recovery quantity, speed, and time, which can be referenced in [17]. For example, Francis and Bekera [28] proposed a resilience metric in

$$r_i(S_P,F_r,F_d,F_o) = S_p \frac{F_r}{F_o}\frac{F_d}{F_o} \qquad (2)$$

that incorporates the resilience capabilities and the time to recover, in which S_p is the speed recovery factor, F_o is the original stable system performance level, F_d is the performance level immediately after the disruption, F_r is the performance at a new stable level after recovery efforts have been exhausted. While these newly proposed metrics are not yet widely applied in the power system, traditional reliability evaluation metrics are still in use. Panteli and Mancarella [29] used the loss of load frequency (LOLF) and loss of load expectation (LOLE) to evaluate the effectiveness of different resilience-enhancing measures.

The result of the evaluation can also be in different time scales. For example, the resilience triangle can be evaluated based on a single event, and also evaluated over a long period of time by Monte Carlo simulation. Ouyang *et al.* [30] introduce a time-dependent expected annual resilience metric as the ratio of the real performance curve to the targeted performance curve. Watson *et al.* [22] provide a resilience framework that is based on the probability distribution of the expected economic loss from a specific type of disruptive events.

C. Resilience Evaluation Framework

From the analysis above, the concept of resilience can be interpreted from different perspectives according to the researcher's preference or priority. In this paper, we provide a comprehensive power system resilience evaluation framework, as shown in Fig. 5. This framework emphasizes the idea underlying resilience evaluation without addressing the technical details. According to the framework, the very first step to evaluate resilience is to identify the extreme events, as resilience is event specific, e.g., a hurricane-resilient system may fail in earthquake. Then, the researchers can choose or construct their own resilience metrics in the form of time of restoration, the load shedded, or the area under a certain performance function. After that, evaluation methodologies can be chosen and the fault consequences can be calculated accordingly. To do so, the spatial–temporal influence of the event on the resilience of the power infrastructure needs to be adequately modeled. It may be evaluated in one fault scenario, producing a concrete resilience measurement value, or in multiple fault scenarios in forms of expected value, probability distribution, etc. The quantitative metrics should be able to reflect the consequence of a certain disruptive event or the effectiveness of the resilience measures. They can overcome the shortcoming of reliability evaluation by incorporating the resilience strategies in the evaluation process. The result can reflect the effectiveness resilience planning and operation in the long run.

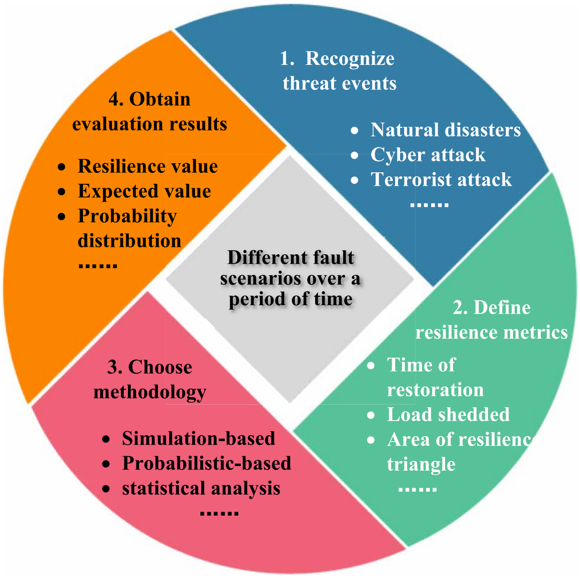


Fig. 5. ***Power system comprehensive resilience framework.***

IV. RESILIENCE IMPROVEMENT METHOD

Resilience evaluations provide quantification methods for the power systems that can identify strengths and weaknesses and propose resilience improving strategies in the power system. In response to the increasing scale and severity of disruptions, utilities have initiated significant infrastructure improvements in the power system. Predominantly, these actions seek to prevent the disruptions by increasing construction standards and system protection level [31]. However, the complexity of the power system and the scale of extreme events bring particular challenges for decision makers. One reason is that measures based on previous disasters do not necessarily ensure protection from unexpected future disaster scenarios; the other is that the balance between the system resilience level and the cost needs to be achieved. Therefore, the investment for boosting resilience usually falls into two different aspects: the system hardening and operational resilience strategies, or known as hard and soft resilience. The suitable roadmap for improving power system resilience should combine both of them to optimize the investment to build a more resilient power system. More details about the resilience strategies can be found in [29], [32], and [33].

A. Resilience Strategies—System Hardening

System hardening is defined as the physical changes to the utility's infrastructure to make it less susceptible to extreme events. Hardening measures usually require large amount of investment. Some common hardening practices are summarized as follows:

- undergrounding the distribution/ transmission lines;
- upgrading poles with stronger, more robust materials;
- elevating substations and relocating facilities;
- redundancy in transmission and distribution system.
- tree trimming/vegetation management.

Hardening measures improve the durability of transmission and distribution systems. For example, after 2008 Southern China snow storm, higher ice-resistant transmission line and transmission tower design standards with ice melting facilities have been widely adopted in the snowstorm-prone areas. As hardening the system is usually costly, and in many cases one hardening strategy can be only effective to a certain type of events, resilience measures must also rely on the fast-developing smart grid technologies.

B. Resilience Strategies—Smart Grid Technology

Smart grid technologies can improve the overall efficiency of the power system operation, and increase power system visibility and system response to faults and outages. These technologies enable the power system to fast locate power outages and restore loads more efficiently. With the ongoing efforts on smart grid and smart distribution system, there will be more operational strategies available for the resilient power system, such as:

- risk assessment and management for evaluating and preparation;
- disaster assessment and priority setting;
- installation of DER or other onsite generation units;
- accurate estimation of the natural disaster location and severity;
- fault location, isolation, and service restoration;
- demand side management;
- microgrid island operation;
- advanced control and protection schemes.

Among the smart grid technologies, advanced metering infrastructure (AMI) can alert the utility grid of outage information in real time. Automatic switches allow the utility grid to isolate the outage and to reroute a blackout area to power supply. Today, utilities build upon smart grid technology to deal with increasing extreme events. Furthermore, the resilience of microgrids have been proven during Hurricane Sandy and the Sendai microgrid during the Great East Japan Earthquake [34]. Microgrids are able to maintain power supply to critical customers, or even support main grid splitting and recovery during a contingency [34]. In addition, distributed generator (DG) can be backup generators in the form of controllable fossil fuel generators, energy storages of electricity, heating, and fuels. For critical loads, DG of diverse energy supply can help to increase the system resilience, as is indicated in the example in [34].

C. Resilience Strategies—Distribution System Resilient Load Restoration Framework

Historical data indicate that 90% of the power outages have their roots in the distribution system. Therefore, a lot of research efforts concentrate in the distribution level [31]. Fast and efficient restoration is a key step to increase the resilience of distribution systems, and resilience strategies at the distribution level are more urgently needed. In this section, we propose a resilient load restoration algorithm in the distribution system through backup DG and reconfiguration after the extreme event occurs and the faults are identified, located, and isolated. Reconfiguration has traditionally been the main means to restore supply right after a fault happens. When the fault is isolated by switches, the load in the fault affected areas could be picked up by tie switches to reconnect to other normally operating feeders. At the same time, the increasing penetration rate of DG in the distribution system also enhances the ability of DGs to perform load restoration. Now intentional islanding of DGs is critical in providing power supply to important loads in the distribution system in the previous disasters [35]. Wang *et al.* [36] proposed a multistage restoration problem that adopted a heuristic optimization algorithm to restore the system through reconfiguration and DG islanding. Specifically, Li *et al.* [37] and Zhang and Chen [38] proposed heuristic and exhaustive search algorithms to find the optimal islands. A mixed-integer linear programming was employed in [39] where every controllable DG will form an islanded microgrid after faults happened. A method to reformulate the microgrid formulation problem in resilient distribution networks was presented in [40].

In this paper, we propose an optimal DG islanding strategy considering reconfiguration after multiple faults in the distribution system. The main contributions of this method are as follows. 1) In the proposed method, the reconfiguration and DG islanding can be optimized simultaneously to obtain the DG islanding scheme with minimal load shedding. 2) The reconfiguration for a radial distribution system after multiple faults is considered. Besides, whether a controllable DG goes into islanding operation is decided optimally. 3) The model is a mixed-integer second-order cone programming and solved by traditional optimization method.

Once line faults happen from hurricane or earthquake, the radial topology of the power system will partition into several islands by faulted components, some of which have DGs or tie switches connected to other areas, and some are isolated blackout areas. For the former, the island can be redirected to other feeders and be supplied from the transformers; or they can form a DG island and be sustainable for a period of time on its own regardless of outside faults. For the latter, the area has to be shut off and the load will be shedded. An example is given in Fig. 6, where the dotted lines indicate

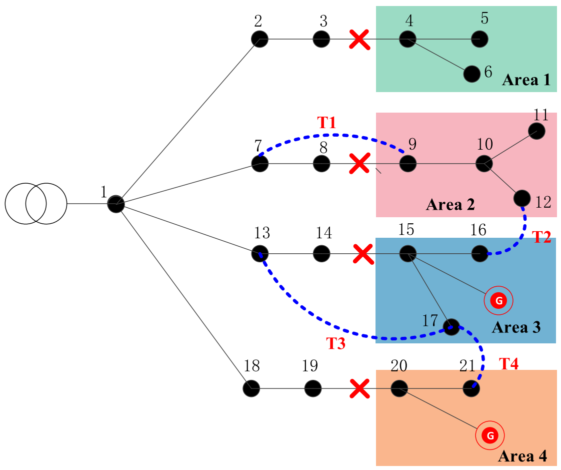


Fig. 6. ***Distribution system after multiple faults.***

the tie switches. According to Fig. 6, after multiple faults, the following types of areas can be formed:

1) area 1 is an isolated load cluster without DG, and the customers are forced to suffer the load shedding;
2) area 2 is an area without DG, but with tie switch, and this area can either redirect to the main grid or connect with other areas that have DG inside;
3) area 3 and area 4 contain DGs, and they can either form two islands, each supplied by one DG, or reconnect with the main grid through T3, or form a DG cluster by closing T4.

In our flowchart in Fig. 7, it is assumed that the distribution system is equipped with tie switches, sectionalizing switches, and DGs. When disaster happens, the system is split into several unconnected areas by faults, as shown in Fig. 6. Those buses connected with the main transformer will not be interfered, while DG can restart to operate in island mode and supply connected loads. Then, by reconfiguration, an optimal island formation scheme that minimizes shedded load can be achieved. After the disaster, the system will return back to normal when the failed components are repaired. In this section, an optimal island partition method is proposed. This method will optimally decide if each DG should go into island mode, form DG clusters with other DG, or work in grid-connected mode.

In this method, the following assumptions are made: 1) a balanced three-phase alternating current (ac) power flow is considered, hence the distribution system is represented by a single-phase equivalent; and 2) the radial topology must be maintained. In addition, it is assumed that every controllable DG can form its own island and serve as the root bus on an island, or they can operate connected to the main grid or with other DGs. The isolated unsupplied island must go into island operation while sustaining a radial structure. Therefore, the first step is to identify the potential root buses. Take Fig. 6 as an example; we know that buses 1, 15, and 20, as well as one bus in area 1, are potential root buses.

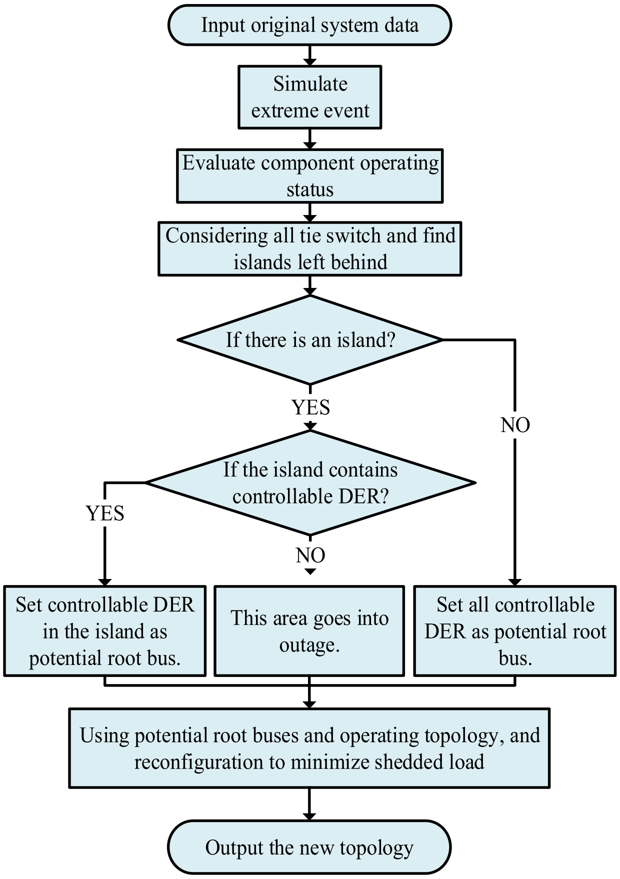


Fig. 7. ***Flowchart of resilient load restoration mechanism.***

The aim is to search the optimal island partition result that can lead to the minimal load shedding. To facilitate load restoration, reconfiguration is also considered. Two sets of 0-1 integer decision variables are adopted, which are: 1) $z, z_{ij} = 1$ when line ij is closed, otherwise $z_{ij} = 0$; and 2) $\gamma, \gamma_k = 1$ when the kth potential root bus is chosen as the root bus, otherwise $\gamma_k = 0$.

Let w_j denote the priority weight associated with the load at bus j. Then, the objective function can be explicitly formulated as (3) to maximize the total priority-weighted loads picked up, such that

$$\max \; \sum_{j\in B} w_j P_{L,j}. \tag{3}$$

A distribution network is usually operated radially and can be formed by a set of recursive equations, called branch flow formulation [41]. Let $G = (B, E)$ represent the connected graph, where B is the set of buses and E is the set of branches. For each bus i, let V_i be the complex bus voltage, for each line ij, I_{ij} is the complex current from, and $r_{ij} + jx_{ij}$ is the complex impedance. F is the set of lines that go out of operation. R is the set of the potential root buses.

To simplify notation, let $l_{ij} := |I_{ij}|^2$ and $u_i := |V_i|^2$. For each line (i,j) with the direction from bus i to j, H_{ij} and G_{ij} indicate the real and reactive power flow from sending point i to j, and correspondingly the real and reactive power flowing from ending point j to i is $-(H_{ij}-r_{ij}l_{ij})$ and $-(G_{ij}-x_{ij}l_{ij})$, respectively. If the branch is closed, the voltage difference of this branch is constrained by power flow and the branch flow should be limited; otherwise, the voltage difference is arbitrary and the branch flow must be zero. The following equations give the power flow constraint

$$\begin{cases} P_{DG,j}-(P_{L,j}-P_{S,j}) = \sum_{s\in\delta(j)} H_{js}-\sum_{i\in\pi(j)} H_{ij} \\ Q_{DG,j}-(Q_{L,j}-Q_{S,j}) = \sum_{s\in\delta(j)} G_{js}-\sum_{i\in\pi(j)} G_{ij} \end{cases}, \quad \forall j\in B \tag{4}$$

$$u_j = u_i - 2\left(r_{ij}H_{ij}+x_{ij}G_{ij}\right)+\left(r_{ij}^2+x_{ij}^2\right), l_{ij}\forall (i,j)\in E \tag{5}$$

$$H_{ij}^2+G_{ij}^2 = l_{ij}u_i, \forall (i,j) \in E \tag{6}$$

Then

$$P_{DG,j}^{\min}\le P_{DG,j}\le P_{DG,j}^{\max},\ Q_{DG,j}^{\min}\le Q_{DG,j}\le Q_{DG,j}^{\max},\quad \forall j\in DG \tag{7}$$

is the DG output limit, and

$$(V_j^{\min})^2\le u_j\le (V_j^{\max})^2,\quad \forall j\in B\backslash R \tag{8}$$

$$(V_j^{\min})^2+[1-(V_j^{\min})^2]\,\gamma_j\le u_j\le (V_j^{\max})^2 + [1-(V_j^{\max})^2]\,\gamma_j,\quad \forall j\in R \tag{9}$$

give voltage limit at each bus, which makes sure that voltage of the root bus is kept at 1 p.u. The line current limit is given by

$$0\le l_{ij}\le z_{ij}\left(I_{ij}^{\max}\right)^2,\quad \forall (i,j)\in E \tag{10}$$

and the status of the faulted line is set by

$$z_{ij}=0,\quad \forall (i,j)\in F \tag{11}$$

The following equation

$$0\le P_{S,j}\le P_{L,j},0\le Q_{S,j}\le Q_{L,j},\quad \forall j\in B \tag{12}$$

limits the load that will be shedded.

In the model, DG is the set of DGs; $P_{L,j}$ and $Q_{L,j}$ are the load demands at each bus; $P_{S,j}$ and $Q_{S,j}$ are the loads that will be shedded at each bus; $\pi(j)$ and $\delta(j)$ are the sets of all parent buses and children buses of bus j.

According to graph theory, a sufficient and necessary condition for radiality is as follows: 1) each subgraph is a connected graph; and 2) the number of branches equals the number of nodes minus the given number of subgraphs [42]. To guarantee the radiality constraint, a single commodity flow method will be used based on the above two conditions [43]. Assuming a fictitious network with the same topology structure and the same connectivity with the original power system, in the fictitious network, root buses are power sources while all the other load buses have unit load demands. Thus, the satisfaction of fictitious load at each bus in the fictitious network implies that at least one path exists between the "power source" bus and the load, so in this way the topology must be connected. Notably, the source can be chosen at any bus in each island. In this work, we choose the DG bus/main transformer in each area to be the potential "source" bus. Thus, we have

$$-P_j=\sum_{s\in\delta(j)}T_{js}-\sum_{i\in\pi(j)}T_{ij} \tag{13}$$

$$P_j=1,\ \forall j\in B\backslash R \tag{14}$$

$$-M\,\gamma_j+1\le P_j\le M\cdot\gamma_j+1,\quad \forall j\in R \tag{15}$$

$$-M\cdot z_{ij}\le T_{ij}\le M\,z_{ij},\quad \forall (i,j)\in E \tag{16}$$

where T_{ij} is the power transferred on the line (i,j) in the fictitious network; P_j is the fictitious load; M is a large number. Equations (14) and (15) can guarantee that the fictitious load of each bus is kept at 1 except for the root buses.

To achieve the second condition, we can give the following simple equation as:

$$\sum_{(i,j)\in E} z_{ij} = N_b-\sum_{k=1}^{|R|}\gamma_k \tag{17}$$

where N_b is the total number of buses. Notably, since there may be islands without DG or with more than one DG, the number of islands is not fixed. Thus, the total number of islands is not predetermined but optimized. Finally, the proposed model can be formulated as

$$\max\ \sum_{j\in B} w_j P_{L,j} \tag{18a}$$

$$\text{s.t operation constraints: (4)–(12)} \tag{18b}$$

$$\text{topology constraints: (13)–(17)} \tag{18c}$$

Note that the nonlinear constraint (6) is a set of nonconvex quadratic equality constraints. To solve the nonlinear integer optimization problem, a second-order cone relaxation is adopted [41]. For (6), conic relaxation can be employed to relax the quadratic equalities into inequalities, yielding

$$H_{ij}^2+G_{ij}^2\le l_{ij}u_i,\quad \forall (i,j)\in E \tag{19}$$

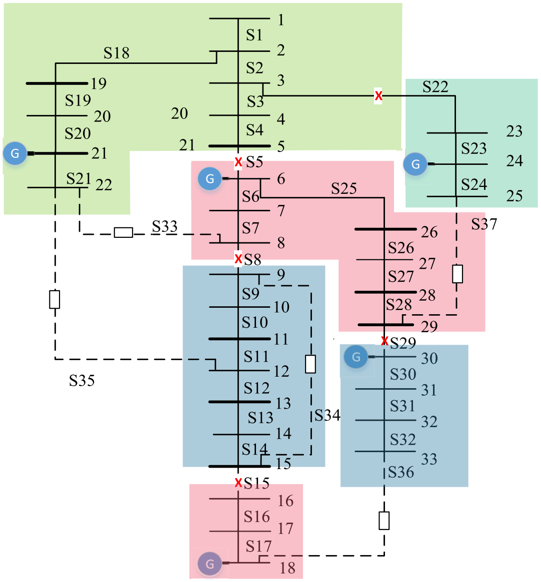
The model in (18) is a mixed-integer second-order cone program (MISOCP), for which the global optimal solution can be found by commercial solvers.

V. CASE STUDY

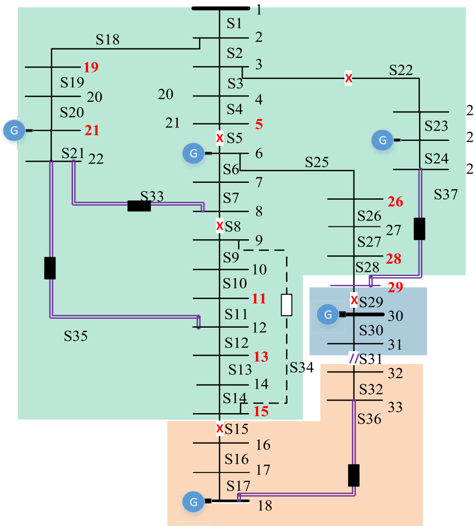
In this section, the proposed resilient load restoration algorithm is applied to two systems: one IEEE 33-bus system and one real Chinese urban distribution system. Multiple line faults are randomly generated for each test system. The computational tasks were performed on a personal computer with Intel Core i7 Quad-Core Processor (3.40 GHz) and 16-GB RAM, and the proposed method was solved by the GUROBI commercial solver. The case study serves as an insightful example to validate the importance of adopting smart distribution technologies in improving power system resilience.

A. Test System—IEEE 33-Bus System

In this case study, an IEEE 33-bus system is taken as the test system to study the resilience enhancement strategy. There are multiple faults within the test system, as shown in Fig. 8(a). The whole system load is 3.7150 MW+2.3 MVar. In this section, the fast restoration algorithm proposed under a deterministic hazard scenario is analyzed. In this system, a total of five DGs are installed, and each is 0.3 MVA. Assume that the five DGs are all controllable, therefore they can all go into island operating mode. It is assumed that five line faults take place and cut the system into six separate areas, as illustrated in Fig. 8(a). By the fast restoration method, the new topology was sketched in Fig. 8(b), where two DG islands are formed and DGs at buses 6, 21, and 24 operate connected to the main grid.



a) System right after faults happen



b) Optimal island formation

Fig. 8. ***The original IEEE 33-bus system with five line failures.***

Initially the lost load is 2.9850 MW, 80.35% of the total active load. The total capacity of the DG is 1.5 MVA, 40.38% of the total active power load. Buses 5, 11, 3, 15, 19, 21, 26, 28, and 29 are randomly selected, the weight of which is set to be 3, while the rest of the load weight is set to be 1. Since the main grid does not entirely black out, the main transformer can still supply the loads. The result is summarized in Fig. 9 where the weighted restored loads are compared for optimal load restoration algorithm [case 5)] and cases 1)–4). The cases are as follows:

case 1) system has no tie switches and no DG;
case 2) system has no tie switches but have DG;
case 3) system has tie switches but no DG;
case 4) system has tie switches and DG, each DG forms one island;
case 5) system has tie switches and DG, the DG islands are optimally formed.

It can be seen that without DG and reconfiguration, only 24.18% of the total active load is still supplied by the main transformer. By installing DG, additional 31.76% load is provided. Case 3) shows that with only reconfiguration, 83.42% load can be supplied. Case 4) represents the method proposed by [39], in which every controllable DG forms its own island, because the main grid is still operating, and such a restoration strategy is not optimal, only restoring 66.73% of the weighted load. The optimal situation is achieved by the proposed algorithm, where three areas are formed, and 95.40% of the total active load is restored.

The supplied load at each bus is also plotted in Fig. 10. It can be seen that due to the DG capacity limitation, load shedding has to be taken on the islands formed by DG at buses 16, 18, 30, and 33. By reconfiguration, the rest of the buses can be supplied by the main transformer and DG. Therefore, DGs at buses 6, 21, and 24 operate in parallel with the main transformer.

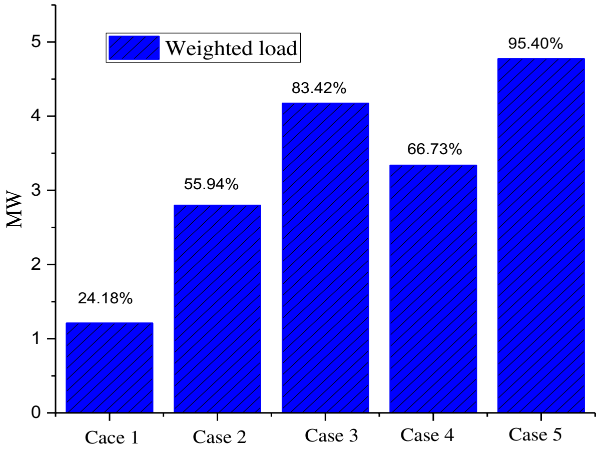


Fig. 9. ***Load restored for the IEEE 33-bus system.***

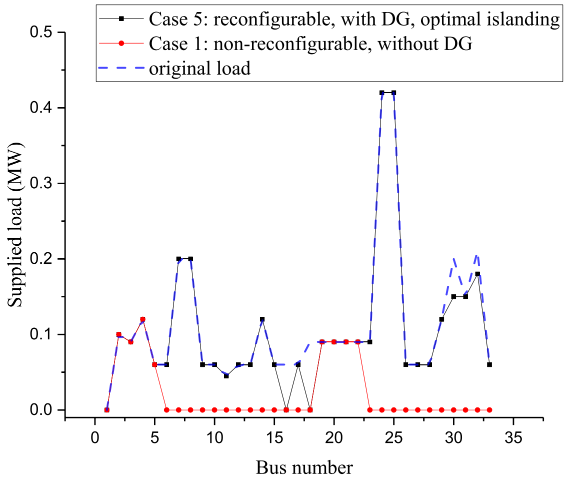


Fig. 10. ***Supplied load at each bus in the IEEE 33 system.***

In addition, except for line capacity and bus voltage constraints, the load restoration is dependent on various other factors, e.g., load weight, fault location, DG location, DG capacity, etc. Therefore, this method is practical to evaluate the maximum possible load restoration level under different disaster scenarios.

B. Test System—Application on a Real System

The proposed method is then applied to a real-world 409-bus system, an urban distribution system in a city of China. There are nine feeders in this system, the system load is 161.2 MW+52.6 MVar, and the base voltage is 10 kV. To test the proposed method, it is assumed that there are eight controllable DGs in the system, each with capacity of 5 MW. The total DG installation is 24.81% of the total active load. There are seven tie switches among the feeders, and 35 sectionalizing switches on the distribution lines. The test is run in four scenarios, where fault restoration is achieved with/without DG or reconfiguration. Topology of the system is shown in Fig. 11. The test results are summarized in Table 1, in which RE denotes reconfigurability, and DG is the existence of DG. In the four rows, Y and N indicate that the system is with or without a certain capability, e.g., the first row is a scenario where the system is nonreconfigurable and has no DG.

Table 1 Result for Load Restoration for the Real-World 409-Bus System

Result		Island num.	Load restored (MW)	Percentage of load restoration (%)	Load shedded (MW)	Time (s)
RE	DG					
N	N	18	105.9155	65.70%	55.2852	0.1741
N	Y	18	117.4343	72.85%	43.7664	0.7728
Y	N	12	131.7209	81.71%	29.4798	0.7216
Y	Y	12	147.5409	91.53%	13.6599	0.4394

Without DG and reconfiguration, the system load loss is 55.2852 MW, 34.30% of the total active load. The restored load was increased by 10.88% and 24.36%, reaching 117.4343 MW and 131.7209 MW, respectively, by DG installation and tie switches. With DG islanding and topology reconfiguration, 91.52% of the system active load can be restored, which is 147.5407 MW.

In summary, the load shedding has been widely recognized as an important resilience metric, and it directly reflects the consequence of the disruptive events and effectiveness of restoration efforts, e.g., in the second test system, even though 34.30% of the load is lost due to line faults, with the proposed resilience measures, 91.52% load can be resupplied despite the distribution lines suffering sustained failures. The application on the test systems further indicates the importance of adopting smart distribution technologies as resilience measures. It should be noted that the proposed method is a deterministic method, while, in reality, there are many uncertainties in the system after an extreme event. Operators should generate multiple load restoration plans for various credible scenarios. This method can also be expanded to accommodate a more realistic situation, by employing robust optimization or stochastic optimization to consider factors such as variability of load and DG outputs.

VI. FUTURE CHALLENGES

In this section, latest resilience technologies, future research directions, and challenges are discussed. Though a resilience enhancing and evaluation framework has been proposed above, power system is a complex system, and there are many practical problems to be solved. The research on resilience is still at an early stage.

A. Modeling Extreme Events

Traditionally, reliability evaluation in the power system has focused on the random component faults from internal causes. Resilience evaluation research, on the other hand, focuses on external, extreme events. In the resilience evaluation framework, to accurately evaluate the consequence of a certain type of events is an essential part of the framework. Faults from extreme events can exhibit different features. For example, faults from natural disasters exhibit time and spatial correlation. For man-made attacks, the targeted attack pattern, mode, and methods might be a topic that most system operators are unfamiliar with. As the system becomes more sophisticated, it is urgent to investigate the frequency with which these extreme events occur, how they act on the power system, and what consequences they can cause.

The complexity of extreme events also highlights the need to categorize the faults by their causes. For the power system, single component fault can be caused by disruptions directly. Besides that, two types of faults can also happen [44]:

- cascading failures, which occur when failure of one component causes the failure of one or more component;

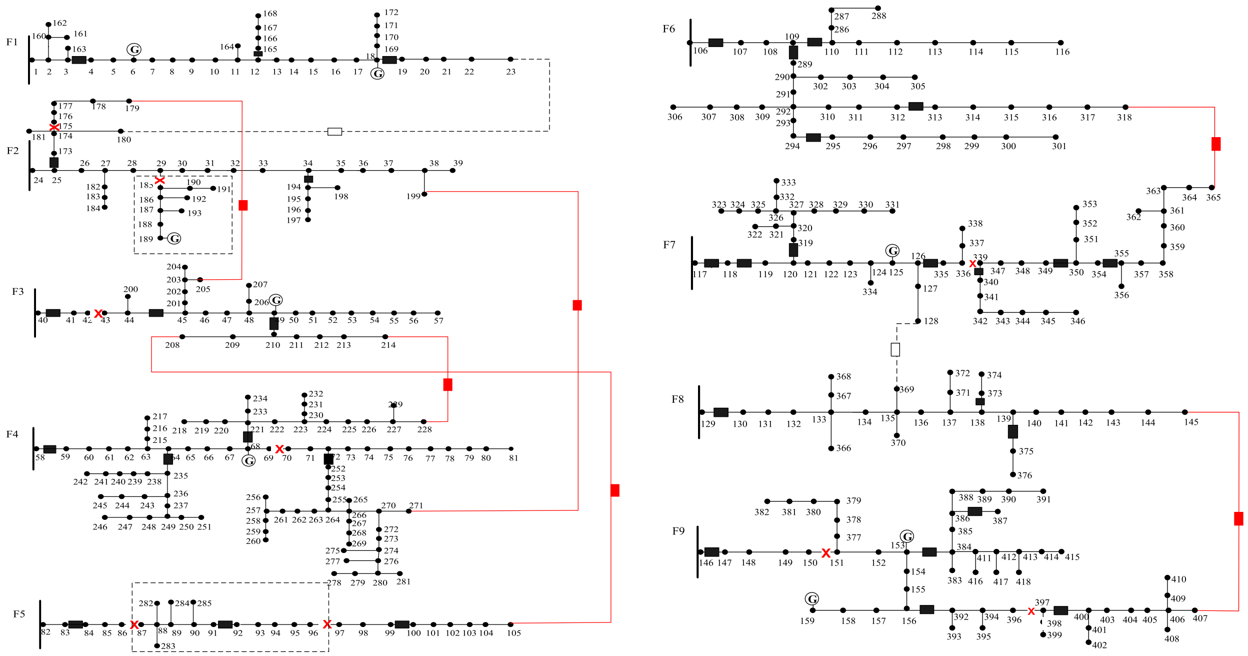


Fig. 11. ***System topology and fault location for the real-world 409-bus system.***

- common-cause faults, which occur when two or more components are affected simultaneously because of some common cause.

There are works on the modeling of faults under extreme events. Li *et al.* [45] provide a framework to model hurricanes in North America; Buldyrev *et al.* [46] discussed the cascading faults between the power system and the cyber system. These works act as useful references for understanding faults in the power system. In addition, resilience strategies should be investigated to fight against the same type of faults.

B. Realistic Barriers in Realizing Resilience

In the previous sections, the result has demonstrated that the optimal load restoration can be achieved fast and accurately by smart distribution technologies. However, this is a simplified method applied in test systems. To employ these advanced resilience strategies, first, the grid codes and industry standards should be established to allow for the DG islanding function, because the islanding functions of DG and microgrids are still limited by many utility grid codes. Fortunately, as microgrids have been validated for their important role in the power system disaster restoration [1], [47], the intentional islanding capability of a microgrid is gradually recognized and regulated in standards, such as IEEE 1547.4 and future International Electrotechnical Commission (IEC) microgrid standards [34]. Then, system hardening and system planning should be carried out to install DG, tie switches, and other necessary facilities. Traditional hardening strategies are essential so the system has redundant components or higher resistance to disruptions. Usually adopted measures include tree trimming, backup generators, optimal resource dispatch, etc. The proposed resilience strategy can be considered as the final step taken after the occurrence of disruptions. These steps can be accomplished through a bottom-up approach, as shown in Fig. 12.

To realize resilience, other barriers exist. First, distribution automation efforts should speed up to increase the power system visibility to achieve higher installation rates of smart meters and automatic switches that allow for a more efficient response to disruptions. What is more, the

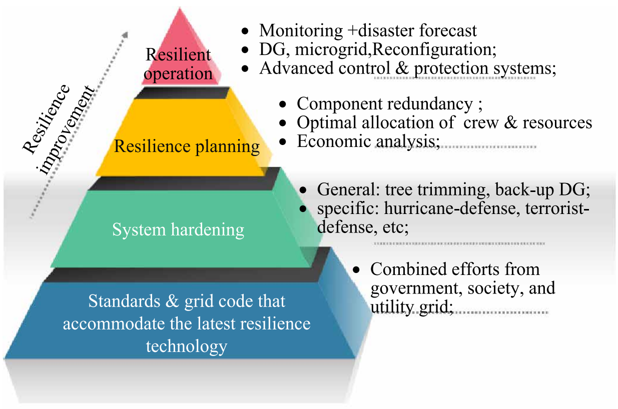


Fig. 12. ***Adopting resilience in the power system.***

protection systems should be updated so as to accommodate the bidirectional energy flow from DG installation. Besides, when major faults happen, the communication system can be heavily damaged as well, as the communication and power system are interdependent systems, and the faults in each system can lead to cascading faults in the other system. The control and communication system that can survive extreme events should be developed, at least for critical loads. Finally, economy is also a key factor in the formation of the dynamic microgrids. To form DG islands, the root bus should be a controllable DG. The DG might be a customer installation or property of the utility grid, and it is not possible that it can supply all customers. Therefore, the market regulation of the distribution system should also be cautiously designed.

C. Interdependence Among Critical Infrastructures

Power, transportation, oil, natural gas, and water systems are all critical infrastructure systems. In the previous works on power system resilience, the power system has been usually treated as an independent entity, however, the operation of power system constantly influences and is being influenced by other critical infrastructures. Taking notice that there is interdependence among all critical infrastructures in Fig. 13, it has been observed that such interdependence can contribute to the overall complexity of the power system resilience planning, operation, and evaluation. Little [44] has illustrated the interdependence among the electric power system, oil, transportation, natural gas, telecom, and water system. The increase in infrastructural interdependencies could increase the risk of a system failure [46]. Cascading failure and common-cause failure can also happen to the interdependent systems, as discussed in Section VI-A.

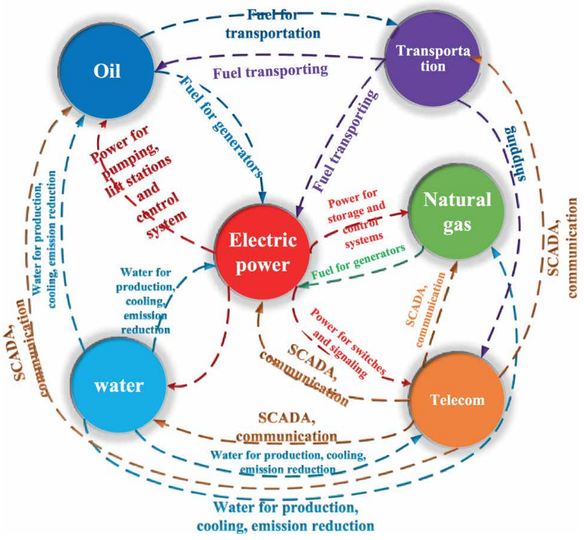


Fig. 13. ***Interdependence among critical infrastructures.***

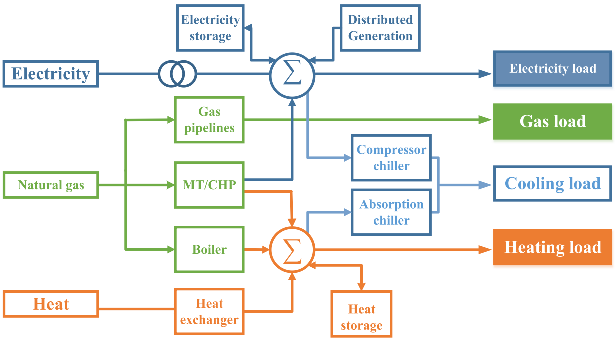


Fig. 14. ***Integrated energy system (IES).***

On the other hand, the increase in infrastructural interdependencies could also potentially mitigate the risk of a system failure. An example is the Roppongi Hills microgrid in Japan during the Great East Japan earthquake [34]. Natural-gas-based Roppongi Hill microgrids were able to maintain supply, because the natural gas supply was not damaged, even though the surrounding network was inoperable for many days.

To go one step further, in the distribution system level, a new concept has emerged recently: the integrated energy system (IES), as shown in Fig. 14. IES combines electricity distribution network, the distributed renewable energy system, the natural gas system, and cooling and heating systems. IES contains multiple subsystems and has a significant multidomain feature. The reliability of IES has been investigated by [48], although the complexity introduced by IES to the resilient planning and operation is a new topic.

VII. CONCLUSION

The establishment of the resilient power system and the improvement of resilience have become an inevitable requirements for the power system. In the face of extreme events, resilience is recognized as an essential characteristic of the critical infrastructures as well as the whole society. Despite the large body of research, resilience is still a new topic in the power system. To clarify ambiguity, in this paper, we conduct a thorough review on the existing works on resilience evaluation and improving technologies of power systems, in which the widely adopted metrics and methodologies are categorized and analyzed. To improve resilience, an effective resilient load restoration method is proposed and its effectiveness is verified. We should bear in mind that resilience research is just beginning, and extreme events will always remain a formidable challenge to the human society in the long run. Future investment, policies, and new technologies are much needed to reinforce resilience in our power system. ■

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