A Review of the Measures to Enhance Power Systems Resilience

Maedeh Mahzarnia, *Student Member, IEEE*, Mohsen Parsa Moghaddam, *Senior Member, IEEE*, Payam Teimourzadeh Baboli, *Member, IEEE*, and Pierluigi Siano, *Senior Member, IEEE*

***Abstract*—Rare and extreme climate events may result in wide power outages or blackouts. The concept of power system resilience has been introduced for focusing on high-impact and low-probability (HILP) events such as a hurricane, heavy snow, and floods. Power system resilience is the ability of a system to reduce the likelihood of blackout or wide power outages due to HILP events. Indeed, in a resilient power system, as the severity of HILP events increases, the rate (but not the amount) of unserved loads diminishes. Suitable measures for managing power system resilience can be classified into three categories in terms of time, known as "resilience-based planning," "resilience-based response," and "resilience-based restoration." The most widely used approaches, methods, and techniques in each of these categories, as well as the future trends for improving the power system resilience are reviewed in this article. The challenges of resilience in power systems with high penetration of renewable energy sources are also discussed in each of these categories.**

***Index Terms*—High-impact and low-probability (HILP) events, power system, renewable energy sources (RESs), resilience-based planning, resilience-based response, resilience-based restoration, resilience evaluation, smart grid technologies.**

Nomenclature

AHP	Analytical hierarchical process.
BSU	Black-start units.
DERs	Distributed energy resources.
DG	Distributed generation.
DOE	Department of Energy.
ENS	Energy not supplied.
ESS	Energy storages systems.
EVs	Electrical vehicles.
HILP	High impact low probability.
MAS	Multiagent systems.
NIAC	National Infrastructure Advisory Council.
NBSU	Nonblack-start units.
NERC	North American Electric Reliability Council.
PCWL	Path combination without loop.
RESs	Renewable energy sources.
SBD	Scenario-based decomposition.
UN	United Nations.
VND	Variable neighborhood decomposition.
WAMS	Wide area measurement systems.

Manuscript received May 28, 2019; revised September 19, 2019 and December 17, 2019; accepted January 8, 2020. Date of publication January 29, 2020; date of current version September 2, 2020. *(Corresponding author: Mohsen Parsa Moghaddam.)*

M. Mahzarnia and M. P. Moghaddam are with the Department of Electrical and Computer Engineering, Tarbiat Modares University, Tehran 14155-143, Iran (e-mail: m.mahzarnia@modares.ac.ir; parsa@modares.ac.ir).

P. T. Baboli is with the Department of Engineering and Technology, University of Mazandaran, Babolsar 47415-416, Iran (e-mail: p.teimourzadeh@umz.ac.ir).

P. Siano is with the Department of Management and Innovation Systems, University of Salerno, Fisciano 84084, Italy (e-mail: psiano@unisa.it).

Digital Object Identifier 10.1109/JSYST.2020.2965993

I. Introduction

POWER system blackout is one of the most challenging issues for both the power industry and consumers because of the high dependence of modern societies on electrical energy and costly procedures for the power system recovery. The loss of the electric power is due to three main reasons [1], [2]: power outages caused by natural disasters, technical problems, and human-made power outages. According to the reports presented by the US Department of Energy, among these sources of blackouts, the role of natural disasters, especially extreme weather events, is more significant [3], [4]. Due to climatic changes in recent decades, the number and severity of weather-related events increased worldwide [5].

By surveying the origins of blackouts, it can be concluded that most of them are caused by low-probability events that impose substantial consequences on power systems, known as high-impact and low-probability (HILP) events [6]. The weather-related events are usually ignored in conventional reliability-based studies [7], [8]. Adding the concept of resilience into classic studies leads to much more realistic modeling of power systems since, in addition to being *reliable*, power grids should also be *resilient* against catastrophic events.

Since the resilience concept has both long-term and short-term features, it can be investigated in three categories in terms of the time of events' occurrence, including resilience-based planning, response, and restoration [9]. Resilience-based planning studies include all long-term measures to improve the resilience of power systems such as plant management, network reconstruction programs, underground cables, and power system hardware designs. Both resilience-based response and resilience-based restoration are considered as short-term activities. The resilience-based response includes a preventive response (e.g., day-ahead measures) and emergency response (real-time measures) [9]. The system recovery measures fall into the category of resilience restoration programs [9]. In this article, some of the most important methods and techniques regarding each of these three clusters are discussed. A relatively holistic classification of studies in this context is shown in Fig. 1.

The incremental penetration of RESs is one of the significant features of today's power systems and their inherent uncertainty affects the power system resilience. Indeed, power outages and blackouts due to unpredictable weather phenomena in power systems with high RESs penetration are regarded as a new

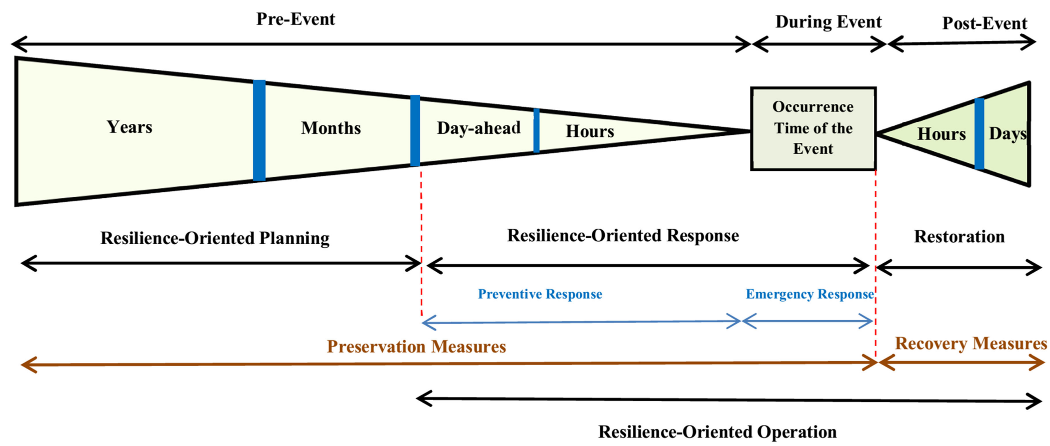

Fig. 1. Classification of power system resilience in terms of the time of the event's occurrence.

challenging issue in this area. It is worth noting that RESs can also be useful to make power systems more resilient, depending on the climate conditions where the system is located (e.g., the Caribbean islands can achieve a high capacity by using RESs to improve the resilience of its power system due to its notable sun radiation, high wind speed, and energy exploitation from the sea [10]–[12]), the dependence of the power system on conventional generation resources, the condition of fuel and water transport infrastructures, etc. [13].

So far, a number of survey papers have been published on power system resilience, however, this subject still requires much research. For example, in [14], the resilience of integrated energy systems, including different infrastructures such as natural gas and district heating networks along with electrical power systems, has been studied. Assessment techniques and frameworks for managing power system resilience have been reviewed in [15] and [16]; however, a detailed classification of resilience studies based on the event's occurrence time (pre-event, during event, and postevent), as well as on the level of power systems (transmission or distribution systems) is needed.

The novel contributions of this article compared to the previous survey studies are as follows.

1) A comprehensive classification of the measures to improve the power system resilience is presented in this article, which is mainly based on the occurrence time of the event. From this new perspective, the resilience measures are classified into two general categories of "preservation measures" and "recovery measures." Preservation measures take place before the event occurrence and involve long-term and short-term measures. Long-term measures are actions that take place from several years to several months before the event occurrence. Short-term measures, that are called "response measures," include "day-ahead preventive actions" and "emergency actions" realized during the event. "Recovery measures" are done immediately after the occurred incident to restore the power system performance to its previous level or to an acceptable level. The measures and strategies for enhancing resilience in each of these categories and subcategories are precisely discussed.
2) Each category of resilience enhancement measures is broken down into subcategories, based on the practicality of measures at different levels of the power system, including transmission and distribution systems (or microgrids).
3) The challenges of resilience in power systems with high RESs penetration, which have not been previously studied, together with efficient measures in each of the categories are analyzed. Also, the future trends of research in this area are discussed.

II. Basics of Power System Resilience

Resilience is a general concept that has many aspects and definitions in different specialized fields such as psychology, economics, biology, and engineering [17], [18].

A general definition of resilience was raised by United Nations in 2009 as "The ability of a system, community or society which is exposed to hazards in order to resist, absorb, accommodate to and recover from the effects of a hazard in an efficient manner, through the preservation and restoration of its essential basic structures and functions" [19].

In 2009, the National Infrastructure Advisory Council (NIAC) presented a description of resilience as the ability to mitigate the negative consequences of "low-frequency, high effect" events [20]. According to NIAC's definition of resilience, it has four main features as follows.

1) *Resourcefulness:* The ability to manage a catastrophe at the time of its occurrence and after that [21].
2) *Robustness:* The ability to absorb an unexpected disastrous event and maintain the performance of a system at an acceptable level [20], [22].
3) *Adaptability:* The ability to learn from the historical data in order to enhance the resilience of a system against similar events that may occur in the future [23].
4) *Rapid recovery:* The ability to restore system elements and provide services after the occurrence of an external shock as fast as possible [20].

In addition to these four main attributes, some other features that are associated with the concept of resilience are as follows.

a) *Redundancy:* A feature to have many substitution options under the stress of a system [24].
b) *Capacity:* The ability to withstand unexpected disturbances in addition to the anticipated ones [20].
c) *Flexibility:* The ability of a system to reorganize itself in a way to keep its performance under imposed changes due to external shocks [25].
d) *Tolerance:* The behavior of a system whether it reduces its functionality or suddenly breaks due to an extreme event [25].

Reliability is an important concept, which is usually confused with resilience. It can be said that reliability is a concept that models the probabilistic behavior of a system to investigate its correct function during exposure to common failures within a specified period. Indeed, reliability is based on the operating point of a power system and has a static nature. Resilience is, instead, based on the trend of network topology changes, which is influenced by the severity of HILP events, and so it exhibits a dynamic behavior. Unlike reliability, resilience is mainly related to the consequences of disturbances without considering the probability of their occurrence [26]. It is worth noting that the reliability of a system can be evaluated without identifying the threats, while the concept of resilience is tied to cope with one or more specific threats. In other words, a system that is resilient against certain types of events may be vulnerable to the other types of events [23]. In [8], and [27]–[29], resilience has been defined as the ability of a system to predict a rare disastrous event, withstand or absorb it, to adapt to its consequences, and quickly recover its performance to an acceptable level after facing such an event. As emphasized in [30], a resilient power system can recover itself using minimum human interventions as quickly as possible.

III. Approaches for Resilience Evaluation

Many studies in the context of resilience have proposed one or more metrics for resilience using different methods [8], [31], [32] that can be generally categorized into qualitative and quantitative approaches [18], [33].

Qualitative approaches for evaluating resilience include conceptual frameworks and semiquantitative indices [18]. Conceptual frameworks are usually based on fundamental elements of the resilience concept such as absorption capacity, adaptive capacity, and recovery capacity [28], [29]. Most of the qualitative approaches are categorized into conceptual frameworks that are based on the main pillars of system resilience including diagnosing and assessment of the disturbance, robustness, consequence mitigation, and adaptability [19], [34]. They are based on the conceptual view of resilience and utilize suitable approaches for detection, adaptability, remediation, and restoration.

Semiquantitative indices are based on assessing specific resilience attributes (e.g., adaptability, resourcefulness, robustness) usually within a range of 0–100 (percentage scale) and a unified index is achieved by their integration [18].

In order to have a clear comparison between the pre-event and postevent resilience levels of a power system, a quantitative assessment is preferred and more attention is paid to it in the related literature. Quantitative methods for resilience assessment can be mainly classified into statistical methods [35], [36], risk-based methods [30], [37], [38], system fragility-based methods [6], graph theory-based methods [29], [39], simulation-based methods [40], and fuzzy logic models [18] and they involve both operational and infrastructure mathematical formulations of resilience metrics [41], [42]. Generally, the model presented in [43] is used for a quantitative evaluation of resilience. It is based on the difference between the real and the ideal performance of a system, which can be represented in different forms as follows:

$$R_1 = \int_{t_0}^{T} (P_i - P_r)\ dt \tag{1}$$

$$R_2 = \sum_{s=1}^{S} \pi_s \cdot \left[\frac{\int_{t_0}^{T} P_r(t)}{\int_{t_0}^{T} P_i(t)} \cdot \frac{T_D}{T - t_0} \right. \tag{2}$$

$$R_3 = S_R \cdot \frac{P_r}{P_i} \cdot \frac{P_e}{P_i}. \tag{3}$$

In (1), resilience is quantified as the difference between the ideal performance level of the system (P_i) and its real performance level (P_r) from the start of the event until the system performance reaches an acceptable level, which is the end of the recovery phase [44]. The expected value of system resilience is defined in [45] with (2), in which π_s denotes the probability of occurrence of failure scenario s out of a total of S failure scenarios, and T_D represents the duration of the event's impact. In addition to P_i and P_r, the recovery speed (S_R), as well as the system performance level immediately after the event occurrence (P_e), are also incorporated in (3) to quantify the resilience [44].

In (1)–(3), the power system performance must be calculated by some metrics appropriate with the concept of resilience. These metrics are typically classified into two categories as follows.

The metrics that indicate the impact of a catastrophe without applying any recovery action [44], [46] are

Total number of customers without electricity power (NC)

$$\mathrm{NC} = \sum_{t=1}^{T} n(t) \tag{4}$$

where $n(t)$ is the number of customers without electricity power on day t.

Loss of load probability (LOLP): the probability of the effective system capacity that does not meet the load demand, and is calculated as

$$\mathrm{LOLP} = P(\mathrm{OC} > \mathrm{RC}) \tag{5}$$

where OC is the outage capacity, and RC is the reserve capacity.

Loss of load expectation (LOLE): the expected number of days/hours in the period T in which the effective capacity of the system does not meet the load demand as written in the following:

$$\mathrm{LOLE} = \mathrm{LOLP} \times T. \tag{6}$$

Loss of load frequency (LOLF): the cumulative frequency of system interruption

$$\mathrm{LOLF} = F(\mathrm{OC} > \mathrm{RC}). \tag{7}$$

Expected energy not supplied (EENS): the expected value of lost energy

$$\mathrm{EENS} = \sum_{\mathrm{RC}-\mathrm{OC}>0} (\mathrm{OC} - \mathrm{RC}) \cdot p(\mathrm{RC})\, t \tag{8}$$

where p(RC) = 1/8760, and t = 8760 in the hourly load model.

Outage cost (OC): the cost imposed on a system due to the outage of some of its loads

$$\mathrm{OC} = \mathrm{EENS} \times \mathrm{VOLL} \tag{9}$$

where VoLL is the prespecified value of lost load in a system.

The metrics that incorporate the impact of recovery actions into the total impact of a catastrophe [47] are

Lost revenue impact (LRI): it is an economic index that represents the lost revenue of the utility

$$\mathrm{LRI} = \sum_{t} \sum_{i} W_i\ (\mathrm{PLN}_i - \mathrm{PLR}_{i,t}) \times D_t \tag{10}$$

TABLE I
DIFFERENT APPROACHES AND METHODS FOR RESILIENCE PLANNING OF POWER SYSTEMS

Resilience planning of power systems			
Distribution Level	Approaches	Hardware-based approaches	[4], [27], [28], [38]–[41]
		Software-based approaches	[38]–[44]
		Combined (hardware and software) approaches	[38]–[41]
	Methods	Stochastic-based	[47]
		Robust optimization-based	[48]
Transmission level	Approaches	Reinforcing the transmission system by hardening the existing elements	[21], [27]
		Developing the transmission facilities by adding new elements and devices	[27], [52], [53]
		Combined approaches	[21], [27], [52], [53]
	Methods	Stochastic-based	[53]
		Robust optimization-based	- - -

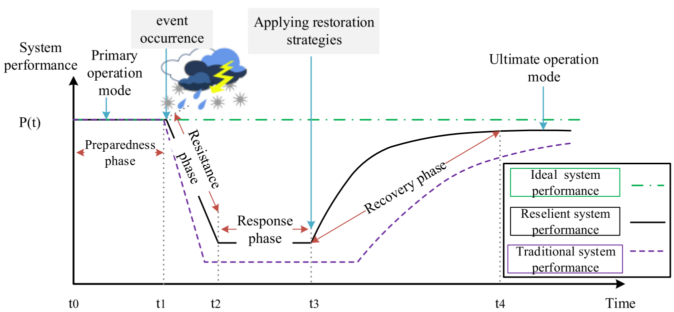

Fig. 2. Illustrative process of changes in the performance level of a resilient power system in the face of a disruptive event.

where PLN_i is the peak load for the *i*th load in normal circumstances, $\mathrm{PLR}_{i,t}$ = peak load for the *i*th load on completion of the *t*th recovery stage, D_t the duration of the *t*th recovery stage, W_i= weighting factor for the *i*th load.

Total restoration (TR): it consists of the total resources used during the recovery process after a catastrophe

$$\mathrm{TR} = \sum\nolimits_t \left[\sum\nolimits_j \mathrm{LC}_j \times \mathrm{WH}_{j,t} + \left(\sum\nolimits_n \mathrm{RC}_n \times \mathrm{RP}_{n,t} \right) + \left(\sum\nolimits_z (\mathrm{OC}_t - \mathrm{OC}_n) \times \mathrm{PG}_{z,t} D_t \right) \right] \quad (11)$$

where LC_j is the hourly cost of labor in category *j*, $\mathrm{WH}_{j,t}$ the working hours per person in category *j* during the *t*th repair stage, RC_n the replacement cost of pieces in category *n*, $\mathrm{RP}_{n,t}$ the number of replacement pieces used in the *t*th repair stage in category *n*, OC_n the generator's operating costs in normal circumstances, OC_t the generator's operating costs during the *t*th stage $\mathrm{PG}_{z,t}$ the power generation of generator z per hour during the *t*th stage.

Recovery resilience (RR): it expresses the total impact of the catastrophe on the utility. The relative priority of TR and LRI is determined by a weighting factor

$$\mathrm{RR} = \frac{\mathrm{LRI} + \mu \times \mathrm{TR}}{\sum_t \sum_i W_i \ (\mathrm{PLN}_i)\, D_t} \quad (12)$$

where μ is the weighting factor demonstrating the relation between supplied energy and recovery resources.

Fig. 2 illustrates how the performance level of a resilient system changes as well as its different phases in the face of a destructive event.

Four main questions for achieving quantitative resilience metrics, as well as the corresponding formulations, are described in [41].

IV. RESILIENCE-BASED PLANNING OF POWER SYSTEMS

Resilience-based planning of power systems can be classified into two main levels, including the distribution and transmission level. Some of the reported approaches and methods are pointed out in Table I, and then discussed.

Strategies for long-term resilience-based planning for distribution systems can be classified into two general categories, including hardware-based and software-based approaches [48]. Hardware-based approaches include following:

1) trimming and management of vegetation [49];
2) hardening the lines, poles, and other components of the distribution network [50], [51];
3) replacing overhead lines by underground cables [32], [51];
4) installing additional lines, breakers, and transformers as well as updating load assignments [39], [50];
5) adding distributed energy resources (DERs) into distribution networks [4], [39], [49], [51], [52].

Software-based approaches include following:

1) determining the priority of the loads at different times and zones [53];
2) operating the distribution system as a multimicrogrid system [49]–[52], [54], [55];
3) moving toward decentralized control by enhancing the distribution automation levels [51];
4) developing smart grid technologies, e.g., advanced metering infrastructure (AMI), telecommunications, distribution management system, and automated demand response programs [49], [51];
5) implementing software-based approaches for resilience planning is more cost effective compared to hardware-based approaches [52], [56], [57]. There are two general software-based methods for resilience planning of distribution systems or microgrids called stochastic-based methods [58]–[60] and robust optimization-based methods.

As an example of stochastic-based methods, a two-stage scenario-based model can be pointed out [58]. In its first stage, the investment plans can be accomplished using some hardware solutions, such as constructing new lines and distributed generator (DG) resources as well as switches allocation. The second stage assesses the improvement of distribution system performance in the operation mode based on the planning measures determined in the first stage.

As mentioned earlier, another approach for optimal planning of distribution networks or microgrids is to use the robust optimization methods, which are usually based on traditional N-K contingency analysis [61], [62]. In this regard, a two-stage model considering the worst scenarios has been proposed in [59], [61], and [63], which is appropriate with the temporal and spatial uncertainty feature of HILP events. A combination of two hardware-based approaches can be used, e.g., hardening the distribution network components along with determining the optimal location of DGs and storages systems.

Some practical measures in resilience-based planning of transmission systems are as follows [26], [32], [64]–[66].

1) Vegetation management and pruning the plants away, which are close to transmission lines.
2) Undergrounding transmission lines to cope with extreme events such as storms.
3) Strengthen the transmission network foundations and elements using more robust types of materials.
4) Moving the infrastructures and transmission lines to places that are less influenced by severe climate-related events.
5) Enhancing the reserve capacity and redundancy by constructing new transmission equipment.
6) Active controlling of the transmission systems using switches for system reconfiguration and flexible ac transmission systems devices for controlling the power flow of transmission lines.

The simultaneous use of some of these actions during the planning of transmission systems can significantly increase the resilience [65], [67].

V. Resilience-Based Response in Power Systems

Maintaining system security and minimizing the operating costs are the two most crucial issues for power systems operation. However, the fulfillment of security constraints should be prioritized over economic constraints. The N-1 criterion is one of the most reliable criteria for system security. An N-1 secure system is a system that is sustainable enough to avoid major outages/blackout [68]. Accordingly, power systems should meet some prerequisites as follows:

1) having enough spinning reserves;
2) having sufficient complementary reserves;
3) optimal allocating both the above types of reserves.

In the operation of a traditional power system, there are several solutions to make a system N-1 (or better) secure, e.g., generation redispatch, shunt injections, controlling switching operations, and regulation of transformers [68]. These solutions are usable, but not sufficient, for the resilience-based operation of power systems. A resilience-based response is the first step of the resilience-based operation involving two types of response when facing catastrophic events. The preventive response is the first type of measure that is usable in the day-ahead scheduling of power systems (or when the predictions warn about a forthcoming event) [9]. Many of the preventive solutions are based on network topology control to predetermine the appropriate topology in a way that the impact of HILP events would be alleviated (defensive islanding, transmission line switching, etc.). After the preventive response, the second type of response, which is called the emergency response, should be implemented [9].

Typically, various solutions for enhancing operational resilience of power systems are known as “resilience resources.”

With the continuing investments in smart grids and smart distribution systems, new operational strategies can be also adopted as resiliency tools. They include vulnerability analysis, innovative self-healing strategies based on the implementation of an AMI and of distribution automation allowing for real-time alert related to an outage, fault location and isolation, service restoration, risk evaluation and management, innovative protection and control schemes, priority setting and disaster assessment, precise estimation of the severity and position of the disaster, installation of onsite generation units, reconfiguration and DG islanding, demand side management, and demand response [44]. Some of the practical resilience resources such as utilizing microgrids, resilience-based unit commitment, transmission line switching, and defensive islanding are discussed in the following.

A. Resilience-Based Unit Commitment

Resilience-based unit commitment is one of the main approaches to improve resilience in the operation of power systems. So far, some mathematical models for resilience-based scheduling of generation resources have been developed. These models are formed based on various algorithms, e.g., decentralized [69] and preventive algorithms [70], which schedule generation resources and storage devices in order to improve power system resilience by covering some amount of uncertainties related to HILP events and renewable resources. Furthermore, some unit commitment models were not initially designed for resilience purposes but can be adapted for that target. For example, security-based unit commitment models proposed in [71] and [72] are suitable for the simultaneous outage of multiple components and can be expanded to reduce the effect of severe weather events and cyber-attacks.

B. Transmission Line Switching

Transmission line switching is another efficient solution for enhancing operational resilience. According to this technique, the power flow of the network can be rerouted by temporarily switching a number of transmission lines. This method is usually implemented in the form of an optimization model based on a dc optimal power flow model in which the maximum number of switching actions (switch ON/OFF) is specified by the network operator. The lines of the network that should be switched to optimally improve the resilience of the power system are defined as variables in an operational planning program and specified after running a defined method [12], [73], [74].

C. Utilizing Microgrids as a Resilience Resource in Power Systems

Many researchers focused on the feasibility of using microgrids in minimizing the interruptions of critical loads. A microgrid can be considered as a resilience resource in three forms including a local resource [75]–[77], a community resource [75], [78], and a restoration resource of the system [75], [78], [79]. The performance of the microgrids in each of these three forms represents a significant contribution to the development of a much more resilient power system [75], [79]. The use of microgrids in power systems can be an effective solution for enhancing the resilience of transmission as well as distribution systems. One of the appropriate techniques for improving resilience by using microgrids is utilizing the percolation theory using an analytical hierarchical process [23]. However, one of the drawbacks of this method is that it only considers the topological factors influencing network resilience. Likewise, a power outage scheme, called hierarchical outage management, can be used to boost the resilience of distribution systems consisting of several microgrids [80]. The algorithm proposed in [80] is based on a novel predictive model that schedules the available resources of the microgrids in the first stage. The unserved loads of the first stage are fed in the second stage using the free capacities of the microgrids' resources. Liu *et al.* [81], in addition to present a resilience index for distribution networks, have demonstrated that using islanding of microgrids can lead to more resilient distribution systems. In [82], a self-healing strategy for islanded microgrids has been presented where two microgrids can be connected to each other under determined conditions and form a larger microgrid, or *vice versa*. Implementing this strategy during or after a malicious event can reduce the load curtailment and improve resilience. Chanda and Srivastava [23], have presented a method to improve the distribution systems resilience by sectionalizing it into several interconnected microgrids. Immediately after an HILP event, the healthy parts of the distribution system are divided into several islanded microgrids in order to prevent the bursting of outages. Instantly after islanding, the critical loads are detected and load shedding is carried out.

The resilience of the transmission system can be improved through resilience analyses based on meshed grids, microgrids networked to each other, or integrated microgrids [56], [81]. However, studies in this context did not investigate the vulnerability of the network when a large number of microgrids are in islanded mode concurrently, and thus, this is an important issue that can be considered in future studies. Furthermore, the resilience of transmission systems can be promoted using automation controllers along with DERs in microgrids [83].

D. Boosting the Resilience of Power Systems Using Defensive Islanding

In addition to the approaches that have been mentioned so far, "defensive islanding" is another efficient solution, which is suitable for improving the transmission system resilience. Defensive islanding is an adaptive algorithm that alleviates the cascading effects of unplanned disastrous events [28], [84], [85]. This method isolates more vulnerable components of a power system by solving a graph-cut problem. In this way, the self-adequate islands are formed, thereby resilience is elevated.

VI. Resilience-Based Restoration of Power Systems

The increasing trend of weather-related events makes the restoration planning of power systems a critical issue. According to the work presented in [86], the main goals of resilience-based restoration include achieving the maximum number of the electrical loads served and the minimum time of power outage duration after catastrophic incidents. There are several measures for resilience-based restoration of power systems. Optimal switching of some components of the power system, such as transmission/distribution lines, is one of the efficient restoration measures [87]. Further, some preventive measures for restoration planning of power systems are presented in [70] and [88] where the stochastic prehurricane models, in which the allocation of resources and the addition of new resources are accomplished using stochastic methods. These kinds of models recognize the critical components located on the way of the upcoming hurricane so that the components will be not damaged and swift restoration of the power system becomes feasible. The strategies for power system restoration have been discussed extensively in the literature. According to [89] and [90], the process of restoration can be divided into three stages, including preparation, system restoration, and load restoration. In the first stage, the status of the system is evaluated. Then, available resources are identified and the locations of sensitive loads with a higher priority are determined. Power system recovery in the condition of major outages is the most crucial goal in the second stage. In [91], the black-start units have been utilized to energize the nonblack-start units (NBSU) so that the generation capacity is maximized. Some constraints have been added for solving the optimization problem in such a way to consider the variation of the severity of the HILP events across the time. In the third stage, restoration of the higher priority loads is conducted so that the amount of energy not supplied (ENS) is minimized [89], [90]. This stage should be performed after restoring the transmission system and when its electrical variables, such as voltage and frequency, become stable. For this purpose, various analytical approaches have been developed, including fuzzy logic-based methods [92], heuristic methods [93], and analytical mathematical methods [94]. It is worth noting that among these approaches, the most accurate results are achieved by using mathematical methods as the first option before fuzzy logic-based methods and heuristic methods, respectively.

Typically, power system recovery after HILP events through traditional restoration strategies may be hard to fulfill [106], [107]. Therefore, developing smart grid technologies, such as advanced network automation techniques, and wide-area measurement systems can play a significant role in power system restoration in the presence of HILP events. Meanwhile, microgrids and DGs are effective smart grid technologies for power systems restoration. Accessibility of generation units is, indeed, one of the most important factors across all stages of power system restoration. Notably, the lack of sufficient generation capacity due to natural disasters can create many challenges in the typical load restoration strategies. For solving this problem, different types of DGs, including fossil-fuel-based DGs as well as RESs can be used by using various models such as multiagent systems (MAS) [108].

Utilizing microgrids is another efficient solution for power system restoration after major outages, as it has been used in [26], [95], [96], and [109]–[111]. Particularly, since it is infrequent that all microgrids of a power system are simultaneously damaged, utilizing them may lead to speed up the process of restoration and improve the resilience. Some methods for utilizing microgrids in power recovery are almost outdated since executing them is very time consuming such as those reported in [112] and [113], which are heuristic-based methods. There are several methods for using microgrids in the process of restoration with lower computational time. The main efficient methods using microgrids for power systems restoration and their drawbacks are summarized in Table II.

TABLE II
RELATED STUDIES ON RESILIENCE-BASED RESTORATION FOR DISTRIBUTION SYSTEMS

Ref.	Proposed Method / Algorithm / Model	Main Approach/ Drawbacks
[95]	Spanning Tree Search Method	Modeling the microgrids as virtual feeders. Not considering the priority of microgrids, the priority of critical loads, and multiple simultaneous failures.
[96]	Modified Spanning Tree Search Method	Modeling the microgrids as virtual feeders.
[97]	A resilience-oriented methodology based on the restoration tree and load group	Considering some dynamic/transient constraints for the problem of critical loads restoration . Not finding the interdependence of critical loads. Modeling the DGs just as synchronous.
[98]	Numerical Simulations	Re-energizing the loads inside the microgrid after power outage using micro-sources. Not paying attention to the modeling of the black start process in unbalanced systems, which should be investigated in future works.
[99]	A decentralized MAS method	The use of islanding method Utilizing EVs based on their V2G facility. The intermittency of renewable energy resources has to be prevailed by some techniques.
[100]	A distributed multi-agent systems method	Switching in distribution systems and development of microgrids.
[101]	Numerical Simulations	Utilizing the EVs in microgrid service restoration.
[102]	A chance-constrained stochastic model	Considering the uncertainties of renewable energy resources and loads.
[86]	A service restoration model based on a mixed-integer linear program	Using networked microgrids in the proposed restoration solution. Not considering dynamic stability of the system in the time of networking the existing microgrids for service restoration.
[103]	Numerical Simulations	Improving the operation and restoration of distribution system using multi-microgrids.
[104]	A two-layer decentralized control method	Utilizing networked microgrids in the restoration process. Not considering the economic and stability aspects of the network which have to be investigated in future works.
[105]	A modified Viterbi algorithm	Achieving the maximum load recovery using the minimum number of switching pair operations.

In [83] and [90], "spanning-tree search" method has been used. In this method, the microgrids are modeled as virtual feeders. One of the drawbacks of the classic spanning-tree search method is that the priority of microgrids or loads is not considered in the process of restoration. The other worse drawback of this method is its incapability to consider multiple simultaneous failures. To overcome these barriers, Wang and Wang proposed a modified spanning tree search method in [84]. In [99] and [100], multiagent based approaches have been used for power system restoration. In [99], an islanding method has been presented to fulfill a decentralized MAS in which electrical vehicles are utilized for microgrid service restoration. Networking multimicrogrids is another efficient method for power system restoration, which is used in [86], [103], and [104]. The "modified Viterbi" algorithm is proposed to achieve the maximum load recovery using the minimum number of switching pair operations in [105]. In [102], a chance-constrained stochastic model is used for power system restoration in which the uncertainties of RES and loads are considered.

VII. RESILIENCE IN POWER SYSTEMS WITH HIGH RESSs PENETRATION

Generally, high penetration of RESs has both positive and negative impacts on the resilience of power systems. Usually, an optimal approach for resilience improvement can be selected by considering both impacts.

The use of renewable energy technologies can be an efficient strategy to enhance the resilience of a power system by considering a diverse portfolio of power generation. The use of diverse RESs can be helpful to smooth their inherent variability and alleviate the vulnerability of power systems to HILP events, particularly, if these resources are distributed depending on water and fuel use needs, climate, and geographical conditions. Sometimes the availability of water needed for power production of hydropower plants, as well as the fueling of conventional resources is disrupted by extreme weather events. In these cases, diversifying the power generation portfolios by including RESs, having low fuel and low water use needs, can play an important role in network power balancing, particularly for the power systems highly dependent on conventional resources. So it can be stated that RESs on-site power generation can improve network resilience at the time of HILP events that can destroy the fuel and water transport infrastructure [13].

Some common issues in resilience studies on power systems with high RESs penetration are as follows:

1) Whether the resilience resources used in traditional power systems are adequate or suitable in the case of power systems with high RESs penetration.
2) The occurrence time of HILP events can become far more critical in the resilience of power systems with high RESs penetration. Regarding the high uncertainty of RESs, if an HILP event occurs at the time of peak load, then power systems may face a significant lack of power generation, and then, an unbalancing between power generation and demand can occur that may lead to major outages.
3) In power systems with high RESs penetration, each HILP event has specific effects on resilience depending on the type of RESs existing in the power system. For example, due to the destructive impacts of hurricanes on turbine blades, wind turbines should be shut down at the time of the event.

The challenges of power systems resilience in the presence of RESs may originate from several factors such as power system topology, the penetration level of RESs, as well as the location and type of HILP events. Major issues regarding integrating RESs into power systems such as those reported in [99]–[108] have direct or indirect effects on power system resilience and mainly would be more challenging for the resilience of power systems with high RESs penetration. A number of these challenges are as follows:

1) unpredictable power generation level of RESs;
2) unintentional islanding;
3) black-start challenges;
4) protection coordination challenges;

5) stability challenges, i.e., frequency regulation, voltage regulation;
6) congestion challenges.

The power generation amount of RESs is not easily predictable due to the variability and uncertainty of these resources. The unpredictability of power generation can lead to weakening two features of resilience, i.e., resourcefulness and adaptability. High penetration of RESs may cause unintentional islanding that may lead to a shortage of robustness and resourcefulness and consequently a diminution of power system resilience. Black-start and protection challenges, particularly in high penetration of RESs, usually have adverse effects on system recovery. By increasing the number of RESs in power systems, stability and congestion challenges would be more critical, and robustness, as well as resilience, will be at risk. Accordingly, power system resilience in presence of high penetration of RESs should be improved using appropriate measures such as promoting fast, responsive energy-storage systems (ESS) as well as using novel technologies to acquire much more robust RESs.

A. Resilience-Based Planning of Power Systems With High RESs Penetration

The planning of power systems with high RESs penetration requires new approaches to achieve greater resilience against HILP events. Generally, the solutions of resilience-based planning for power systems with high RESs penetration can be categorized as first, resources planning including generation and demand-side resources [114], [115]; second, transmission and distribution planning including development of transmission and distribution lines and construction of new substations, which are compatible with RESs [116]–[118].

Some appropriate approaches that can be considered in resilience-based resource planning of power systems with high penetration of RESs are described in the following.

According to [119] and [120], anticipating the power generation amount of RESs, particularly at the time of HILP events is not simple. Developing new methods and technologies to improve load forecasting as well as RESs power generation forecasting to determine appropriate reserve capacity can promote the adaptability feature of the power system. Hence, power system resilience in the condition of high penetration of RESs will be enhanced.

The approach proposed in [120] and [121] to offset the variability and uncertainties of RESs is based on the investment in dispatchable generation sources besides nondispatchable generation sources. This approach provides mixed generation sources for a power system and so amplifies its resourcefulness, which is one of the main features of resilience. The planning solutions used in [117], [122], and [123], i.e., embedding modern equipment for ESS, batteries, and pumped storage power plants, as well as considering the quick activation of advanced demand-side resources, can be developed in order to provide enough resourcefulness to achieve a resilient power system with high penetration of RESs.

Proactive planning for transmission and distribution systems in a power system with high RESs penetration is one of the main pillars of resilience-based planning. Generally, RESs are usually installed as close as possible to load centers. However, if RESs are placed at faraway sites, a greater emphasis should be on strengthening and constructing new transmission lines. Furthermore, specific protection devices should be designed that are appropriate with high penetration of RESs and have the capability to deal with HILP events.

Planners should first identify which type of HILP events are more likely to occur in the under-study area and after that should recognize the effects of these specific HILP events. In the next step, the most appropriate network topology should be determined to deal with these incidents. These topologies should be designed so that their susceptibility is minimal to these malicious events. Pure resilience-based planning does not considerably focus on economic issues; so the administrative costs of the proposed plans may be extremely high. Therefore, it is suggested that planners offer optimal policies to enhance resilience considering a reasonable budget.

The operation (day-ahead) planning of power systems with high RESs penetration has an intricate procedure, due to the uncertainty of power generation in this type of resources. This procedure becomes more complicated when deciding on a resilience-based scheme for power system operation. Generally, the resilience of power systems can be studied from two perspectives including resource-driven and network-driven studies. By increasing the penetration of RESs, resource-driven resilience studies become much more critical [124]. In the day-ahead operation planning, by anticipating the possible severity of the event, the operators can decide how to schedule the generation units including RESs.

Several solutions should be used to have a resilient power system in the condition of high penetration of RESs. First of all, the prediction tools and methodologies should be promoted to have a more accurate prediction of power system loads and power generation amount of RESs at the occurrence time of HILP events [73], [117]. To achieve a more accurate forecast of the power generation from RESs, real-time and historical environmental factors should be considered. In the literature, many techniques have been proposed that prove the fact that using weather-data driven methods can considerably improve the prediction accuracy of renewable power generation and reduce the uncertainty of RESs. A weather-driven probabilistic graphical technique based on Gaussian conditional random field approach has been proposed in [73] in order to precisely forecast the power generation from RESs. Yang *et al.* [125] and Dowell *et al.* [126] revealed that considering the spatial correlations among the solar farms along with the local meteorological measurements results in a more improved forecast of solar power generation. It has been demonstrated that considering long-term, short-term, and even immediate-short-term climate changes can be significantly effective in accurately predicting wind power generation [126], [127].

Furthermore, in order to offset the lack of power generation arising from HILP events and/or the intermittency of RESs, many measures can be utilized, e.g., traditional units besides RESs [120], [128] [118], [129], novel demand response programs [118], [129], and actual or virtual kinds of ESS [117], [123].

System restoration after HILP events is an important issue that becomes further critical in presence of high RESs penetration. The restoration of power systems with only conventional resources is fulfilled in a manageable time so that network restoration is coordinated with generation restoration. In contrast, restoration of power systems with high RESs penetration is tough to manage. In this regard, according to IEEE standard 1547, there should be 5-min intervals between disconnection of RESs and their automatic reconnection [130], [131].

Therefore, many technical issues may arise in the process of restoration of power systems with high RESs penetration. Since most of these problems may be so complicated to be solved, novel solutions should be presented for this purpose in future research works.

VII. Conclusion and Future Research Directions

The most critical gaps in the context of power systems resilience can be summarized as follows.

1) In most of the previous studies, only one of the resilience dimensions has been investigated, such as the restoration time or the number of interrupted loads. Therefore, these works are more similar to vulnerability studies than resilience ones.
2) In the major studies, which have been conducted on distribution systems resilience, the network topology has been neglected. Considering distribution systems topologies can lead to a realistic evaluation of the economic benefits of the use of resilience resources.
3) The impacts of high renewables penetration on power systems resilience in each of the three phases, including planning, response, and restoration have not been studied explicitly so far. In this article, at first, different approaches for enhancing the resilience of power systems in each of its three phases are reviewed. Afterward, the effects of high penetration of renewables on power system resilience have been briefly discussed. However, this issue requires more fundamental research.

Some future research trends about power system resilience are as follows.

1) The power system has been generally viewed as an independent entity in previous works on power system resilience; however, the operation of the power system influences and is seriously affected by the performance of other critical infrastructures such as telecommunication, transportation, water, oil, and natural gas systems. It is therefore required to assess the interdependence among different infrastructures that affect the process of restoring a power system after HILP events, as well as providing a holistic approach to simultaneously manage the resilience of all the infrastructures given as follows.
2) Developing metrics and indices, which can lead to a comprehensive evaluation of power system resilience by taking into account all various dimensions of resilience.
3) Investigating the cost effectiveness of resilience improvement strategies when a power system faces an HILP event with severe consequences and identifying the appropriate models to incorporate the economic issues in the solutions for improving power system resilience.
4) Providing holistic and flexible models that enable the power system operator to optimally use resilience resources in any event.
5) Developing new strategies for resilience improvement that are suitable for power systems with a large number of RESs.
6) Exploring the effect of long-term planning of DERs on power system resilience by considering constraints such as the state of health of electrical energy storages and plug-in electric vehicles' batteries.
7) Information and communications technologies are increasingly used in the power system today that increase the need for cyber resilience. It is, therefore, required to develop methods for power systems resiliency that consider the cyber security issues.
8) Using accurate historical data related to the intensities of each event (even with hourly resolution) in any geographic area to select the most appropriate and least-risk resilience improvement solution.
9) In order to identify the most probable HILP events in a region where a power system is located, it will be useful to consider climate models and performing a geospatial analysis to parameterize predictions.

References

[1] A. B. Smith and R. W. Katz, "US billion-dollar weather and climate disasters: Data sources, trends, accuracy and biases," *Natural Hazards*, vol. 67, no. 2, pp. 387–410, 2013.

[2] A. Staudt and R. Curry, "More extreme weather and the US energy infrastructure," Nat. Wildlife Federation Rep., Reston, VA, USA, Rep. 16, 2011.

[3] Y. Wang, C. Chen, J. Wang, and R. Baldick, "Research on resilience of power systems under natural disasters—A review," *IEEE Trans. Power Syst.*, vol. 31, no. 2, pp. 1604–1613, Mar. 2016.

[4] R. J. Campbell, "Weather-related power outages and electric system resiliency," Congressional Res. Service, Washington, DC, USA, Tech. Rep. 7-5700, 2012.

[5] C. Chen, J. Wang, and D. Ton, "Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: An integrated solution," *Proc. IEEE*, vol. 105, no. 7, pp. 1267–1288, Jul. 2017.

[6] M. Panteli, C. Pickering, S. Wilkinson, R. Dawson, and P. Mancarella, "Power system resilience to extreme weather: Fragility modeling, probabilistic impact assessment, and adaptation measures," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3747–3757, Sep. 2017.

[7] P. T. Baboli, "Investigating the impacts of distributed energy resource expansion on flexible and overall reliability indices of hybrid AC-DC microgrid," in *Proc. Power Syst. Comput. Conf.*, 2016, pp. 1–7.

[8] R. Billinton and G. Singh, "Application of adverse and extreme adverse weather: Modelling in transmission and distribution system reliability evaluation," *IEE Proc. Gener. Transmiss. Distrib.*, vol. 153, no. 1, pp. 115–120, 2006.

[9] G. Huang, J. Wang, C. Chen, J. Qi, and C. Guo, "Integration of preventive and emergency responses for power grid resilience enhancement," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4451–4463, Nov. 2017.

[10] "Energy resilience solutions for the Puerto Rico grid," U.S. Dept. Energy, Washington, DC, USA, Tech. Rep., Jun. 2018. [Online]. Available: https://www.energy.gov/sites/prod/files/2018/06/f53/DOE%20Report_Energy%20Resilience%20Solutions%20for%20the%20PR%25

[11] H. H. Alhelou, M. E. Hamedani-golshan, T. C. Njenda, and P. Siano, "Events: Research motivations and challenges," *Energies*, vol. 12, pp. 1–28, 2019.

[12] D. Spiegel-feld, N. A. Bishop, and A. G. Wood, "Clean and resilient power for Caribbean states," Guarini Center, New York, NY, USA, 2018.

[13] S. Cox, E. Hotchkiss, D. Bilello, A. Watson, and A. Holm, "Bridging climate change resilience and mitigation in the electricity sector through renewable energy and energy efficiency: Emerging climate change and development topics for energy sector transformation," Nat. Renewable Energy Lab., Golden, CO, USA, Tech. Rep. NREL/TP-6A20-67040, 2017.

[14] Y. Lin and Z. Bie, "Study on the resilience of the integrated energy system," *Energy Procedia*, vol. 103, pp. 171–176, 2016.

[15] Y. Lin, Z. Bie, and A. Qiu, "A review of key strategies in realizing power system resilience," *Global Energy Interconnection*, vol. 1, no. 1, pp. 70–78, 2018.

[16] F. H. Jufri, V. Widiputra, and J. Jung, "State-of-the-art review on power grid resilience to extreme weather events: Definitions, frameworks, quantitative assessment methodologies, and enhancement strategies," *Appl. Energy*, vol. 239, pp. 1049–1065, 2019.

[17] Y. Y. Haimes, "On the definition of resilience in systems," *Risk Anal.*, vol. 29, no. 4, pp. 498–501, 2009.

[18] S. Hosseini, K. Barker, and J. E. Ramirez-Marquez, "A review of definitions and measures of system resilience," *Reliab. Eng. Syst. Saf.*, vol. 145, pp. 47–61, 2016.

[19] J. H. Kahan, A. C. Allen, and J. K. George, "An operational framework for resilience," *J. Homeland Secur. Emerg. Manag.*, vol. 6, no. 1, pp. 1547–7355, 2009.

[20] A. R. Berkeley, III, M. Wallace, and C. COO, "A framework for establishing critical infrastructure resilience goals," Nat. Infrastruct. Advisory Council, Washington, DC, USA, 2010. [Online]. Available: http://www.dhs.gov/xlibrary/assets/niac/niac-a-framework-for-establishing-critical-infrastructure-resilience-goals-2010-10-19.pdf

[21] E. D. Vugrin, "Critical infrastructure resilience," Sandia National Laboratories, Albuquerque, NM, USA, p. 236, 2016.

[22] T. McDaniels, S. Chang, D. Cole, J. Mikawoz, and H. Longstaff, "Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation," *Global Environ. Change*, vol. 18, no. 2, pp. 310–318, 2008.

[23] S. Chanda and A. K. Srivastava, "Defining and enabling resiliency of electric distribution systems with multiple microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2859–2868, Nov. 2016.

[24] T. D. O'Rourke, "Critical infrastructure, interdependencies, and resilience," *Bridg. Acad. Eng.*, vol. 37, no. 1, pp. 22–29, 2007.

[25] D. D. Woods, "Four concepts for resilience and the implications for the future of resilience engineering," *Rel. Eng. Syst. Saf.*, vol. 141, pp. 5–9, 2015.

[26] M. Panteli and P. Mancarella, "The grid: Stronger, bigger, smarter?: Presenting a conceptual framework of power system resilience," *IEEE Power Energy Mag.*, vol. 13, no. 3, pp. 58–66, May/Jun. 2015.

[27] R. Arghandeh, A. von Meier, L. Mehrmanesh, and L. Mili, "On the definition of cyber-physical resilience in power systems," *Renewable Sustain. Energy Rev.*, vol. 58, pp. 1060–1069, 2016.

[28] M. Panteli, D. N. Trakas, P. Mancarella, and N. D. Hatziargyriou, "Boosting the power grid resilience to extreme weather events using defensive islanding," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2913–2922, Nov. 2016.

[29] S. Chanda and A. K. Srivastava, "Quantifying resiliency of smart power distribution systems with distributed energy resources," in *Proc. IEEE 24th Int. Symp. Ind. Electron.*, 2015, pp. 766–771.

[30] G. Sansavini, "Engineering resilience in critical infrastructures," in *Resilience and Risk*. New York, NY, USA: Springer, 2017, pp. 189–203.

[31] Y. Liu and C. Singh, "A methodology for evaluation of hurricane impact on composite power system reliability," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 145–152, Feb. 2011.

[32] M. Panteli and P. Mancarella, "Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events," *IEEE Syst. J.*, vol. 11, no. 3, pp. 1733–1742, Sep. 2017.

[33] R. Francis and B. Bekera, "A metric and frameworks for resilience analysis of engineered and infrastructure systems," *Rel. Eng. Syst. Saf.*, vol. 121, pp. 90–103, 2014.

[34] A. S. Kahnamouei, T. G. Bolandi, and M.-R. Haghifam, "The conceptual framework of resilience and its measurement approaches in electrical power systems," in *Proc. IET Int. Conf. Resilience Transmiss. Distrib. Netw.*, 2018, pp. 1–11.

[35] H. Liu, R. A. Davidson, and T. V Apanasovich, "Statistical forecasting of electric power restoration times in hurricanes and ice storms," *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 2270–2279, Nov. 2007.

[36] R. Nateghi, S. D. Guikema, and S. M. Quiring, "Comparison and validation of statistical methods for predicting power outage durations in the event of hurricanes," *Risk Anal.*, vol. 31, no. 12, pp. 1897–1906, 2011.

[37] S. D. Guikema, S. M. Quiring, and S. Han, "Prestorm estimation of hurricane damage to electric power distribution systems," *Risk Anal.*, vol. 30, no. 12, pp. 1744–1752, 2010.

[38] S. R. Han, *Estimating Hurricane Outage and Damage Risk in Power Distribution Systems*. College Station, TX, USA: Texas A&M Univ., 2008.

[39] P. Bajpai, S. Chanda, and A. K. Srivastava, "A novel metric to quantify and enable resilient distribution system using graph theory and choquet integral," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 2918–2929, Jul. 2018.

[40] Y. Wang, "Tool to analyze power system security under hurricane threats," Amer. Public Power Assoc., Washington, DC, USA, 2013.

[41] M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou, "Metrics and quantification of operational and infrastructure resilience in power systems," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4732–4742, Nov. 2017.

[42] A. Kwasinski, "Quantitative model and metrics of electrical grids' resilience evaluated at a power distribution level," *Energies*, vol. 9, no. 2, pp. 1–27, 2016.

[43] M. Shinozuka *et al.*, "Resilience of integrated power and water systems," *Seismic Eval. Retrofit Lifeline Syst.*, vol. 1, pp. 65–86, 2003.

[44] Z. Bie, Y. Lin, G. Li, and F. Li, "Battling the extreme: A study on the power system resilience," *Proc. IEEE*, vol. 105, no. 7, pp. 1253–1266, Jul. 2017.

[45] J. Lu, J. Guo, Z. Jian, Y. Yang, and W. Tang, "Resilience assessment and its enhancement in tackling adverse impact of ice disasters for power transmission systems," *Energies*, vol. 11, no. 9, 2018, Art. no. 2272.

[46] R. Billinton and R. N. Allan, "Power-system reliability in perspective," *Electron. Power*, vol. 30, no. 3, pp. 231–236, Mar. 1984.

[47] H. Shayeghi and A. Younesi, "Resilience metrics development for power systems," in *Power Systems*. New York, NY, USA: Springer, 2019.

[48] W. P. Zarakas, S. Sergici, H. Bishop, J. Zahniser-Word, and P. Fox-Penner, "Utility investments in resiliency: Balancing benefits with cost in an uncertain environment," *Electr. J.*, vol. 27, no. 5, pp. 31–41, 2014.

[49] G. Davis, A. F. Snyder, and J. Mader, "The future of distribution system resiliency," in *Proc. Power Syst. Conf. Clemson Univ.*, 2014, pp. 1–8.

[50] A. Barnes, H. Nagarajan, E. Yamangil, R. Bent, and S. Backhaus, "Resilient design of large-scale distribution feeders with networked microgrids," *Electr. Power Syst. Res.*, vol. 171, no. Feb., pp. 150–157, 2019.

[51] Y. Xu, C.-C. Liu, K. P. Schneider, and D. T. Ton, "Toward a resilient distribution system," in *Power Energy Soc. General Meet.* IEEE, 2015, pp. 1–5.

[52] C. Buque and S. Chowdhury, "Distributed generation and microgrids for improving electrical grid resilience: Review of the mozambican scenario," in *Proc. Power Energy Soc. General Meet.*, 2016, pp. 1–5.

[53] P. T. Baboli, "Flexible and overall reliability analysis of hybrid AC–DC microgrid among various distributed energy resource expansion scenarios," *IET Gener. Transmiss. Distrib.*, vol. 10, no. 16, pp. 3978–3984, 2016.

[54] E. Unamuno and J. A. Barrena, "Hybrid ac/dc microgrids - Part I: Review and classification of topologies," *Renewable Sustain. Energy Rev.*, vol. 52, pp. 1251–1259, 2015.

[55] E. Unamuno and J. A. Barrena, "Hybrid ac/dc microgrids - Part II: Review and classification of control strategies," *Renewable Sustain. Energy Rev.*, vol. 52, pp. 1123–1134, 2015.

[56] Z. Li, M. Shahidehpour, F. Aminifar, A. Alabdulwahab, and Y. Al-Turki, "Networked microgrids for enhancing the power system resilience," *Proc. IEEE*, vol. 105, no. 7, pp. 1289–1310, Jul. 2017.

[57] S. D. Manshadi and M. E. Khodayar, "Expansion of autonomous microgrids in active distribution networks," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1878–1888, May 2018.

[58] E. Yamangil, R. Bent, and S. Backhaus, "Resilient upgrade of electrical distribution grids," *Proc. Natl. Conf. Artif. Intell*, vol. 2, pp. 1233–1240, 2015.

[59] K. S. A. Sedzro, A. J. Lamadrid, and L. F. Zuluaga, "Allocation of resources using a microgrid formation approach for resilient electric grids," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2633–2643, May 2018.

[60] A. Gholami, T. Shekari, F. Aminifar, and M. Shahidehpour, "Microgrid scheduling with uncertainty: The quest for resilience," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2849–2858, Nov. 2016.

[61] W. Yuan, J. Wang, F. Qiu, C. Chen, C. Kang, and B. Zeng, "Robust optimization-based resilient distribution network planning against natural disasters," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2817–2826, Nov. 2016.

[62] A. Khodaei, "Resiliency-oriented microgrid optimal scheduling," *IEEE Trans. Smart Grid*, vol. 5, no. 4, pp. 1584–1591, Jul. 2014.

[63] B. Zhang, P. Dehghanian, and M. Kezunovic, "Optimal allocation of PV generation and battery storage for enhanced resilience," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 535–545, Jan. 2019.

[64] R. L. Wilby *et al.*, "A review of climate risk information for adaptation and development planning," *Int. J. Climatol.*, vol. 29, no. 9, pp. 1193–1215, 2009.

[65] H. Nagarajan, E. Yamangil, R. Bent, P. Van Hentenryck, and S. Backhaus, "Optimal resilient transmission grid design," in *Proc. Power Syst. Comput. Conf.*, 2016, pp. 1–7.

[66] Y. Fang and G. Sansavini, "Optimizing power system investments and resilience against attacks," *Rel. Eng. Syst. Saf.*, vol. 159, pp. 161–173, 2017.

[67] H. Nagarajan, R. Bent, P. Van Hentenryck, S. Backhaus, and E. Yamangil, "Optimal resilient transmission grid design," in *Proc. Power Syst. Comput. Conf.*, 2016, pp. 1–7.

[68] F. Alvarado and S. Oren, "Transmission system operation and interconnection," Nat. Transmission Grid Study, U.S. Dept. Energy, Washington, DC, USA, Tech. Rep., pp. A1–A35, 2002. [Online]. Available: http://www.kves.uniza.sk/kvesnew/dokumenty/EEAJ/T3_3_TS_ operation.pdf

[69] N. Rahbari-Asr, Y. Zhang, and M.-Y. Chow, "Cooperative distributed energy scheduling for storage devices and renewables with resiliency against intermittencies," in *Proc. Ind. Electronics IEEE 25th Int. Symp.*, 2016, pp. 612–617.

[70] A. Arab, A. Khodaei, S. K. Khator, K. Ding, V. A. Emesih, and Z. Han, "Stochastic pre-hurricane restoration planning for electric power systems infrastructure," *IEEE Trans. Smart Grid*, vol. 6, no. 2, pp. 1046–1054, Mar. 2015.

[71] R. Eskandarpour, A. Khodaei, and J. Lin, "Event-driven security-constrained unit commitment," in *Innovative Smart Grid Technol. Conf. IEEE Power Energy Soc.*, 2016, pp. 1–5.

[72] R. Eskandarpour, A. Khodaei, and J. Lin, "Event-driven security-constrained unit commitment with component outage estimation based on machine learning method," in *Proc. North Amer. Power Symp.*, 2016, pp. 1–6.

[73] P. Dehghanian, B. Zhang, T. Dokic, and M. Kezunovic, "Predictive risk analytics for weather-resilient operation of electric power systems," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 3–15, Jan. 2019.

[74] P. Dehghanian, S. Aslan, and P. Dehghanian, "Quantifying power system resilience improvement using network reconfiguration," in *Proc. IEEE 60th Int. Midwest Symp. Circuits Syst.*, 2017, pp. 1–4.

[75] K. P. Schneider, F. K. Tuffner, M. A. Elizondo, C.-C. Liu, Y. Xu, and D. Ton, "Evaluating the feasibility to use microgrids as a resiliency resource," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 687–696, Mar. 2017.

[76] R. H. Lasseter *et al.*, "CERTS microgrid laboratory test bed," *IEEE Trans. Power Del.*, vol. 26, no. 1, pp. 325–332, Jan. 2011.

[77] M. B. Nurpeisova, O. A. Sarybaiev, and O. S. Kurmanbaiev, "Study of regularity of geomechanical processes development while developing deposits by the combined way," *Nauk. Visnyk Natsionalnoho Hirnychoho Universytetu*, vol. 5, no. 4, pp. 30–36, 2016.

[78] K. P. Schneider *et al.*, "Evaluating the feasibility to use microgrids as a resiliency resource," *Trans. Smart Grid*, vol. 8, no. 2, pp. 687–696, 2017.

[79] K. Balasubramaniam, P. Saraf, R. Hadidi, and E. B. Makram, "Energy management system for enhanced resiliency of microgrids during islanded operation," *Electr. Power Syst. Res.*, vol. 137, pp. 133–141, 2016.

[80] H. Farzin, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Enhancing power system resilience through hierarchical outage management in multi-microgrids," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2869–2879, Nov. 2016.

[81] X. Liu, M. Shahidehpour, Z. Li, X. Liu, Y. Cao, and Z. Bie, "Microgrids for enhancing the power grid resilience in extreme conditions," *IEEE Trans. Smart Grid*, vol. 8, no. 2, pp. 589–597, Mar. 2017.

[82] K. P. Schneider, F. K. Tuffner, M. A. Elizondo, C.-C. Liu, Y. Xu, and D. Ton, "Evaluating the feasibility to use microgrids as a resiliency resource," in *Proc. IEEE Power Energy Soc. General Meeting*, 2016.

[83] P. Penkey, M. Alla, B. K. Johnson, and T. R. McJunkin, "Improving transmission system resilience using an automation controller and distributed resources," in *Proc. Resilience Week (RWS)*, 2016, pp. 89–94.

[84] Z. Wang and J. Wang, "Self-healing resilient distribution systems based on sectionalization into microgrids," *IEEE Trans. Power Syst.*, vol. 30, no. 6, pp. 3139–3149, Nov. 2015.

[85] L. R. Phillips *et al.*, "Agents and islands: Managing a power system before, during, and after transition to the islanded state," in *Proc. Syst. Syst. Eng. IEEE/SMC Int. Conf.*, 2006, p. 6.

[86] A. Arif and Z. Wang, "Service restoration in resilient power distribution systems with networked microgrid," in *Power Energy Soc. General Meet.*, 2016, pp. 1–5.

[87] J. C. López, J. F. Franco, and M. J. Rider, "Optimisation-based switch allocation to improve energy losses and service restoration in radial electrical distribution systems," *IET Gener. Transmiss. Distrib.*, vol. 10, no. 11, pp. 2792–2801, 2016.

[88] A. Arab, A. Khodaei, Z. Han, and S. K. Khator, "Proactive recovery of electric power assets for resiliency enhancement," *IEEE Access*, vol. 3, pp. 99–109, 2015.

[89] L. H. Fink, K.-L. Liou, and C.-C. Liu, "From generic restoration actions to specific restoration strategies," *IEEE Trans. Power Syst.*, vol. 10, no. 2, pp. 745–752, May 1995.

[90] M. M. Adibi and L. H. Fink, "Overcoming restoration challenges associated with major power system disturbances-restoration from cascading failures," *IEEE Power Energy Mag.*, vol. 4, no. 5, pp. 68–77, Sep./Oct. 2006.

[91] W. Sun, C.-C. Liu, and L. Zhang, "Optimal generator start-up strategy for bulk power system restoration," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1357–1366, Aug. 2011.

[92] S.-J. Lee, S.-I. Lim, and B.-S. Ahn, "Service restoration of primary distribution systems based on fuzzy evaluation of multi-criteria," *IEEE Trans. Power Syst.*, vol. 13, no. 3, pp. 1156–1163, Aug. 1998.

[93] S. Toune, H. Fudo, T. Genji, Y. Fukuyama, and Y. Nakanishi, "Comparative study of modern heuristic algorithms to service restoration in distribution systems," *IEEE Trans. Power Del.*, vol. 17, no. 1, pp. 173–181, Jan. 2002.

[94] P. T. Baboli, M. Shahparasti, M. P. Moghaddam, M. R. Haghifam, and M. Mohamadian, "Energy management and operation modelling of hybrid AC–DC microgrid," *IET Gener. Transmiss. Distrib.*, vol. 8, no. 10, pp. 1700–1711, Oct. 2014.

[95] J. Li, X.-Y. Ma, C.-C. Liu, and K. P. Schneider, "Distribution system restoration with microgrids using spanning tree search," *IEEE Trans. Power Syst.*, vol. 29, no. 6, pp. 3021–3029, Nov. 2014.

[96] N. J. Anuranj, R. K. Mathew, S. Ashok, and S. Kumaravel, "Resiliency based power restoration in distribution systems using microgrids," in *Proc. Power Syst. IEEE 6th Int. Conf.*, 2016, pp. 1–5.

[97] Y. Xu, C.-C. Liu, K. P. Schneider, F. K. Tuffner, and D. T. Ton, "Microgrids for service restoration to critical load in a resilient distribution system," *IEEE Trans. Smart Grid*, vol. 9, no. 1, pp. 426–437, Jan. 2018.

[98] C. L. Moreira, F. O. Resende, and J. A. P. Lopes, "Using low voltage microgrids for service restoration," *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 395–403, Feb. 2007.

[99] A. Sharma, D. Srinivasan, and A. Trivedi, "A decentralized multiagent system approach for service restoration using DG islanding," *IEEE Trans. Smart Grid*, vol. 6, no. 6, pp. 2784–2793, Nov. 2015.

[100] C. Chen, J. Wang, F. Qiu, and D. Zhao, "Resilient distribution system by microgrids formation after natural disasters," *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. 958–966, Mar. 2016.

[101] C. Gouveia, C. L. Moreira, J. A. P. Lopes, D. Varajao, and R. E. Araujo, "Microgrid service restoration: The role of plugged-in electric vehicles," *IEEE Ind. Electron. Mag.*, vol. 7, no. 4, pp. 26–41, Dec. 2013.

[102] H. Gao, Y. Chen, Y. Xu, and C.-C. Liu, "Resilience-oriented critical load restoration using microgrids in distribution systems," *IEEE Trans. Smart Grid*, vol. 7, no. 6, pp. 2837–2848, Nov. 2016.

[103] F. O. Resende, N. J. Gil, and J. A. Lopes, "Service restoration on distribution systems using multi-microgrids," *Int. Trans. Electr. Energy Syst.*, vol. 21, no. 2, pp. 1327–1342, 2011.

[104] Z. Wang, B. Chen, J. Wang, and C. Chen, "Networked microgrids for self-healing power systems," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 310–319, Jan. 2016.

[105] C. Yuan, M. S. Illindala, and A. S. Khalsa, "Modified viterbi algorithm based distribution system restoration strategy for grid resiliency," *IEEE Trans. Power Del.*, vol. 32, no. 1, pp. 310–319, Feb. 2017.

[106] Y. Liu, R. Fan, and V. Terzija, "Power system restoration: A literature review from 2006 to 2016," *J. Mod. Power Syst. Clean Energy*, vol. 4, no. 3, pp. 332–341, 2016.

[107] G. M. Karagiannis, S. Chondrogiannis, E. Krausmann, and Z. I. Turksever, *Power Grid Recovery After Natural Hazard Impact*. Publications Office Eur. Union: Brussels, Belgium, 2017.

[108] X. Xu, J. Mitra, N. Cai, and L. Mou, "Planning of reliable microgrids in the presence of random and catastrophic events," *Int. Trans. Electr. Energy Syst.*, vol. 24, no. 8, pp. 1151–1167, 2014.

[109] J. Varela *et al.*, "The best of IGREENgrid practices: A distribution network's contribution to resiliency," *IEEE Power Energy Mag.*, vol. 13, no. 3, pp. 81–89, May/Jun. 2015.

[110] A. Castillo, "Risk analysis and management in power outage and restoration: A literature survey," *Electr. Power Syst. Res.*, vol. 107, pp. 9–15, 2014.

[111] L. Che, M. Khodayar, and M. Shahidehpour, "Only connect: Microgrids for distribution system restoration," *IEEE Power Energy Mag.*, vol. 12, pp. 70–81, Jan. 2014.

[112] W. P. Luan, M. R. Irving, and J. S. Daniel, "Genetic algorithm for supply restoration and optimal load shedding in power system distribution networks," *IEE Proc. Gener. Transmiss. Distrib.*, vol. 149, no. 2, pp. 145–151, Mar. 2002.

[113] S. Toune, H. Fudo, T. Genji, Y. Fukuyama, and Y. Nakanishi, "A reactive tabu search for service restoration in electric power distribution systems," in *Proc. Evol. Comput. IEEE World Congress Comput. Intell. IEEE Int. Conf.*, 1998, pp. 763–768.

[114] J. A. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins, "Integrating distributed generation into electric power systems: A review of drivers, challenges and opportunities," *Electr. Power Syst. Res.*, vol. 77, no. 9, pp. 1189–1203, 2007.

[115] E. Martinot, "Grid integration of renewable energy: Flexibility, innovation, and experience," *Ann. Rev. Environment Resource*, vol. 41, pp. 223–251, 2016.

[116] M. M. Eissa, "Protection techniques with renewable resources and smart grids - A survey," *Renewable Sustain. Energy Rev.*, vol. 52, pp. 1645–1667, 2015.

[117] I. E. Agency and P. P. S. Programme, “Power system operation and augmentation planning with PV integration: Outcome of the IEA-PVPS task 14’s subtask 3- High penetration PV in power system,” IEA Int. Energy Agency, Paris, France, Tech. Rep. T14-04:2014, 2014.
[118] M. I. Alizadeh, M. Parsa Moghaddam, N. Amjady, P. Siano, and M. K. Sheikh-El-Eslami, “Flexibility in future power systems with high renewable penetration: A review,” *Renewable Sustain. Energy Rev.*, vol. 57, pp. 1186–1193, 2016.
[119] “Power system operation planning with PV integration,” Int. Energy Agency Photovolt. Power Syst. Program., R. I.-P. T14-04, 2014.
[120] A. von Meier, “Challenges to the integration of renewable resources at high system penetration,” Energy Res. Dev. Div. Final Project Rep., California Inst. Energy Environment, Berkeley, CA, USA, Tech. Rep. CEC-500-2014-042, 2014.
[121] P. Nema, R. K. Nema, and S. Rangnekar, “A current and future state of art development of hybrid energy system using wind and PV-Solar: A review,” *Renewable Sustain. Energy Rev.*, vol. 13, no. 8, pp. 2096–2103, 2009.
[122] S. Weitemeyer, D. Kleinhans, T. Vogt, and C. Agert, “Integration of renewable energy sources in future power systems: The role of storage,” *Renewable Energy*, vol. 75, pp. 14–20, 2015.
[123] P. D. Lund, J. Lindgren, J. Mikkola, and J. Salpakari, “Review of energy system flexibility measures to enable high levels of variable renewable electricity,” *Renewable Sustain. Energy Rev.*, vol. 45, pp. 785–807, 2015.
[124] B. Zhang, “Resilient grid operation by integrating photovoltaic generation, mobile electric vehicle battery energy storage, and fixed battery energy storage,” 2017.
[125] C. Yang, A. A. Thatte, S. Member, and L. Xie, “Multitime-scale data-driven spatio-temporal forecast of photovoltaic generation,” *IEEE Trans. Sustain. Energy*, vol. 6, no. 1, pp. —104–112, Jan. 2015.
[126] J. Dowell, S. Member, P. Pinson, and S. Member, “Very-short-term probabilistic wind power forecasts by sparse vector autoregression,” *IEEE Trans. Smart Grid*, vol. 7, no. 2, pp. —763–770, Mar. 2016.
[127] N. Amjady, F. Keynia, and H. Zareipour, “Short-term wind power forecasting using ridgelet neural network,” *Electr. Power Syst. Res.*, vol. 81, no. 12, pp. 2099–2107, 2011.
[128] F. Mwasilu, J. J. Justo, E. K. Kim, T. D. Do, and J. W. Jung, “Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration,” *Renewable Sustain. Energy Rev.*, vol. 34, pp. 501–516, 2014.
[129] S. Kakran and S. Chanana, “Smart operations of smart grids integrated with distributed generation: A review,” *Renewable Sustain. Energy Rev.*, vol. 81, pp. 524–535, 2018.
[130] “Performance of distributed energy resources during and after system disturbance, voltage and frequency ride-through requirements,” North Amer. Electric Rel. Corp., Atlanta, GA, USA, 2013.
[131] Y.-K. Wu, T.-C. Lee, T.-Y. Hsieh, and W.-M. Lin, “A review of technical requirements for high penetration of wind power systems,” *J. Power Energy Eng.*, vol. 2, no. 12, pp. 11–17, 2014.