IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 21, 2019, accepted November 4, 2019, date of publication November 8, 2019, date of current version November 20, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2952362

Proactive Resilience of Power Systems Against Natural Disasters: A Literature Review

MOHAMED A. MOHAMED[1,2], (Member, IEEE), TAO CHEN[3], (Member, IEEE), WENCONG SU[4], (Senior Member, IEEE), AND TAO JIN[1], (Senior Member, IEEE)

[1]Department of Electrical Engineering, Fuzhou University, Fuzhou 350116, China
[2]Electrical Engineering Department, Faculty of Engineering, Minia University, Minia 61519, Egypt
[3]Bradley Department of Electrical and Computer Engineering, Virginia Tech, Arlington, VA 22203, USA
[4]Department of Electrical and Computer Engineering, College of Engineering and Computer Science, University of Michigan–Dearborn, Dearborn, MI 48128, USA

Corresponding authors: Wencong Su (wencong@umich.edu) and Tao Jin (jintly@fzu.edu.cn)

This work was supported in part by the Chinese National Natural Science Foundation under Grant 51977039 and Grant 51807031, and in part by the Research Fund for International Young Scientists of the National Natural Science Foundation of China under Grant 51950410593.

ABSTRACT The increase in power outages caused by high-impact low-probability events, such as extreme weather-related climate variation events, is the main reason behind studying power system resilience. However, the concepts of resilience as well as the proactive procedures that can be carried out to address these events are such have not so far been satisfactorily investigated notwithstanding their growing benefits. This paper exhibits a review of the current research on power system resilience; which predominantly focuses on proactive resilience against natural disasters. Firstly, it gives a theoretical framework to acquire insights into power system resilience and its key features. Secondly, it presents frameworks for proactive resilience of power systems with a spotlight on the extreme weather events and their effect. Finally, various strategies for preparing, hardening and enhancing proactive resilience with a focus on microgrids for improving power system resilience are reviewed.

INDEX TERMS Power system resilience, proactive management, natural disasters, microgrid, extreme weather, resilience enhancement.

I. INTRODUCTION

Increasing the intensity and repetition of blackouts due to extreme weather events and severe damage to people and the economy is as yet the weak point of the electrical infrastructures [1], [2]. For example, in 2008 almost 2.8 million subscribers in the Houston region suffered from several weeks of a power outage due to Hurricane Ike. At this time, the total damage caused by this Hurricane in the coastal and inland areas of the USA was about \$ 24.9 billion [3]. In the same year, China suffered a severe snowstorm, which led to damage of 2000 substations and a breakdown of 8500 towers resulting in power outages in 13 provinces and 170 cities [4]. During the summer of 2010-2011, Queensland, Australia, affected by large-scale flooding led to significant damage of 6 substations, several transformers, poles and overhead transmission lines [5]. Meanwhile, nearly 150,000 customers have experienced power outages. In 2011, about 4.4 million families in Japan affected by 7-9 days outages due to the Tohoku earthquake and tsunami. The early reports in this time estimated the losses insured by this earthquake by \$ 14.5 - \$ 34.6 billion [6]. In 2012, the northeastern states of USA struck Hurricane Sandy, which destroyed more than 100,000 main electrical wirings; likewise, many transformer substations have exploded and submerged several substations. This caused an interruption of nearly 7 million subscribers [7]. In Jiangsu, China, about 135,000 families suffered from power outages due to a tornado in 2016 [8]. In 2018, USA experienced 6 weather-related events lead to losses which estimated by \$1 billion for each [9]. In USA, the economic loss caused by weather-related damages is estimated from \$20-\$55 billion, annually [10]. In UK, there are about 10 yearly outages events, due to transmission network faults and about 50% of them are attributable to the weather [11]. Although the low eventuality nature of extreme weather events, it has serious results and predominantly causes successive impacts on the whole system. Recently, there has been a marked increase in power system disturbances-related extreme weather, for example, according to the report of the European Network of Electric Transport Operators (ENTSO-E) [12], 30-60% of the reasons of power outages in North were occurred by environmental factors.

The associate editor coordinating the review of this manuscript and approving it for publication was Yu Liu.

Meanwhile, in the period 1980-2017, the EU member states estimated the economic losses caused by severe weather conditions by 83% of total monetary losses which evaluated by €426 billion [13]. Over time, systems become more unpredictable and interconnected, which makes them more vulnerable to disasters. Moreover, the impacts of extreme weather events present exceptional difficulties to these systems [14]. Hence, the improvement of alleviation techniques that go beyond major disaster risk transfer is the way for effective disaster management. However, the issue of the effective response to weather-related natural disasters is still at an immature stage [15]. These facts are motivating numerous nations to investigate the power systems resilience and their impact on the consequences of these disasters, which have become a major concern for utilities and governments. Lately, the study of power system resilience has acquired prevalence, however, it is as yet not fully stable, and the innovative work in this field is yet under implementation. The inspiration of this paper relied on the necessity to exhibit an exhaustive study of the latest work on the resilience of power systems that at most focuses on the proactive resilience of power systems against high-impact low-probability events (HILP). In fact, malicious attacks are also related to HILP events and have calamitous damage incurred by unprecedented man-made cyber-physical attacks. However, the main focus in this paper is on proactive resilience against extreme weather events (i.e. natural hazards) as one of the authentic reasons that threaten the resilience of power systems. The main contributions of this paper are summarized as the following:

- This paper gives a broad survey of the concepts and characteristics of power system resilience and the understanding of extreme weather events and their awful effects.
- The terms ‘‘reliability’’, ‘‘flexibility’’, ‘‘resistance’’ ‘‘robustness’’ and ‘‘resilience’’ are sometimes utilized incorrectly, since these are extraordinary and sometimes complementary properties. This paper describes the differences between these terms with regard to power systems.
- Differentiate between blackouts and disasters in the context of power systems.
- A power system resilience framework, which gives a generic comprehension of the investigation of power system resilience, is likewise exhibited.
- One major contribution of this paper is introducing a comprehensive survey on current research of enhancement strategies of proactive resilience of power systems. Among these strategies, the utilization of microgrids (*MGs*) for improving power system resilience, which has been extensively presented in this paper.
- The paper highlights the proactive strategies based-machine learning for resiliency enhancement of power systems. In addition, compared between the optimization-based and machine learning-based methods for proactive strategies design.
- The paper highlights the role of renewable energy integration in enhancing power system resilience.
- Furthermore, it gives several recommendations for future research opportunities.

II. THE CONCEPT OF RESILIENCE

A. THE CONCEPT OF RESILIENCE FOR GENERAL APPLICATIONS

The term resilience originates from ‘‘resiliō’’, which is a Latin word alludes to an object’s ability to recover or regain to its authentic form or situation after exposure. The founding definition of resilience was in 1973 by Holling, where it was recognized as a proportion of ‘‘the continuity of system and its capacity to retain disturbance and continue to preserve the similar connections among population and state factors’’ [16]. Ever after this definition, a wide range of definitions was developed, resulting in the absence of a standard definition. The concept of resilience has constructed in many fields (i.e. safety, organizational, socio-economic and economic management) [17]. For example, in relation to natural catastrophe as earthquakes, storms and cyclones; the local resilience has been defined as the capability to endure a severe event without misfortunes, loss of profitability or life, and less significant support from others [18]. Another definition originated by the Multidisciplinary and National Center of Earthquake Engineering Research (MCEER) appropriate for any critical infrastructure (CI), and comprises the robustness, redundancy, resourcefulness and rapidity, and referred to as ‘‘4Rs’’ [19]. In general, resilience as described by Madni and Jackson [20] is a multi-aspect capacity, comprises avoidance, absorption, adaptation and recovery from disturbances.

B. THE CONCEPT OF POWER SYSTEM RESILIENCE

With regards to power systems such as a CI, the image is more blurry. Recently, a few efforts by various associations around the world, such as UK Energy Research Center (UKERC), UK Cabinet Office, and National Infrastructure Advisory Council (NIAC), have been presented to define power system resilience. The UKERC [21] defines resilience as the capability of the power system to endure turbulence and continue to provide energy services to subscribers. Furthermore, a resilient power system can recuperate quickly from disturbance and present substitutional plans for fulfilling energy service requirements. The Cabinet Office, UK [22], defined a CI’s resilience as the capability for anticipation, absorption, adaptation, and recovers quickly from a troublesome occasion. Upon this definition, the main properties of a resilient CI are resistance, reliability, redundancy, and response/recovery as described in Fig.1. The NIAC [23] provides a more general definition of resilience applicable to any CI, which is also considering the capability to realize lessons through subversive events and adjust the operation and CI framework to restrain or alleviate the effect of the same events in the future. The major resilience properties by NIAC are robustness, resourcefulness, quick recovery, and adaptability.

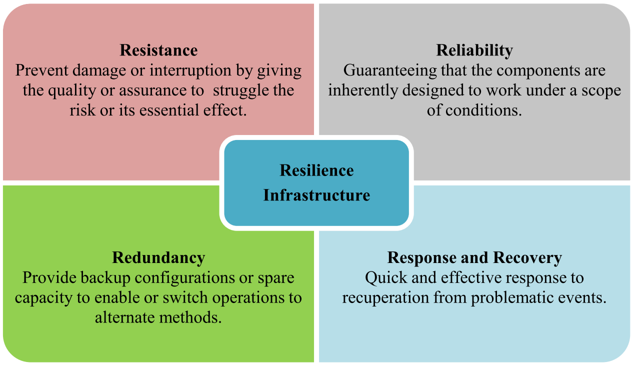

FIGURE 1. The basic characteristics of a resilient system by the U.K. cabinet office [22].

The Stockholm Resilience Centre (SRC), Stockholm, Sweden recognized resilience as the system's ability to continually change and adapt yet stay within critical thresholds [24]. The Intergovernmental Panel on Climate Change (IPCC), defined resilience as the system's capability and it's components to anticipate, absorb, adjust, or recuperate from the effect of a dangerous occasion inadequate and effective manner, with a guarantee that its basic infrastructure and functions are maintained, restored or improved [25]. The Presidential Policy Directive (PPD-21) defined resilience as the system's capability to prepare and adjust to varying situations, withstand and rapid recovery from turbulence [26], [27]. The United Nation-International Strategy for Disaster Reduction (UN-ISDR), Geneva, Switzerland recognized resilience as the system's ability, which is likely to be exposed to risks of adaptation, through resistance or change to attain and retain a reasonable performance. This is achieved by the system's capacity to organize itself and extend this by learning from previous disasters, in order to better protect the future and ameliorate risk mitigation actions [28].

Other attempts have been performed by various authors worldwide to define the power system resilience such as in [29], Overbye et al. defined it as the system capability to gradually deteriorate under increasing exertion and rapidly recover to its predicament secure status. In [30] resilience is outlined as the robustness and recovery qualities of system infrastructure and operations that evade the service interruption during the unusual and dangerous events. Concerning the contextual meaning of the resilience of power systems, the authors in [31] defined it as the system's capability to anticipate, absorb and recover from the serious occasions in a convenient and successful way. In other words, it alludes to the system's capability to recover rapidly after a disaster, or in general the ability to anticipate the exceptionally and HILP events, the rapid recovery from troublesome occasions, and absorbing experiences to adjust its infrastructure and operations, to prevent or alleviate the effect of same future events. Haimes [32] characterized resilience as the capacity of the framework to withstand a noteworthy disturbance inside adequate retrogression parameters and recoup inside a worthy time and composite expenses and dangers. Willis and Lola in [33] featured four characteristics of the power system resilience (i.e. the service-state response to disturbances, design, operation, system responses and time scale). Aven [34] characterized resilience as the vulnerability about and seriousness of the outcomes of the movement given the event of any sorts of occasions.

The definitions of power system resilience are interminable; however most of them focus on the capability for anticipation, absorption and quickly recover from external, HILP shocks. Table 1 presents a synopsis of the general definitions of resilience and their main characteristics. From the above definitions, a resilient power system should have four-basic characteristics (i.e. anticipation, absorption, recovery and adaptability after adverse events), as described in Fig.2 [23]. The anticipation is the system's capability to avert any potential deterioration resulting from severe weather events. The absorption is the system's ability to minimize deteriorations brought about by severe weather events. The recovery is the system's ability to modify its harmed functions resulted from critical weather occasion. The adaptability is a procedure where the system imparts from previous occasions, to enhance its ability, and prepare to the arrangement with the upcoming events.

In [26] the authors showed the difference between resistance and resilience of the system against disaster. They defined system resistance as the ability to withstand disaster invariably, whilst the resilience indicates its ability to "bounce back" to the pre-disaster situation. In the wake of natural disasters and unprecedented attacks, robustness and resilience have become common words in power systems. Robustness refers to the system ability to deal with a particular set of disturbances and maintain its functionality [35]. Robustness infers resistance to change while resilience relies upon flexibility and survivability notwithstanding sudden outrageous events.

With regard to power system reliability, there have been several attempts to distinguish resilience from the concept of reliability. The concept of reliability and characteristics are recognized, and several studies have been recently performed on it, as in [36]. As the construction and operation of the traditional power system have been driven by the main reliability standards of safety and efficiency through normal situations and expected emergencies [37]. Figure 3 shows some key features that distinguish resilience from reliability.

III. POWER SYSTEM RESILIENCE FRAMEWORKS

With regard to environmental change, HILP is becoming increasingly significant as its recurrence, severity and duration are prospected to increment [38]. Thus, the design and operation of the system must be not only reliability oriented, yet additionally resilience-oriented, concentrating on actions that can be considered against HILP events. Hence it was necessary to distinguish between blackouts and disasters with regards to power systems [39]. The blackout happens when a huge extent of the system is impaired by a series of sudden

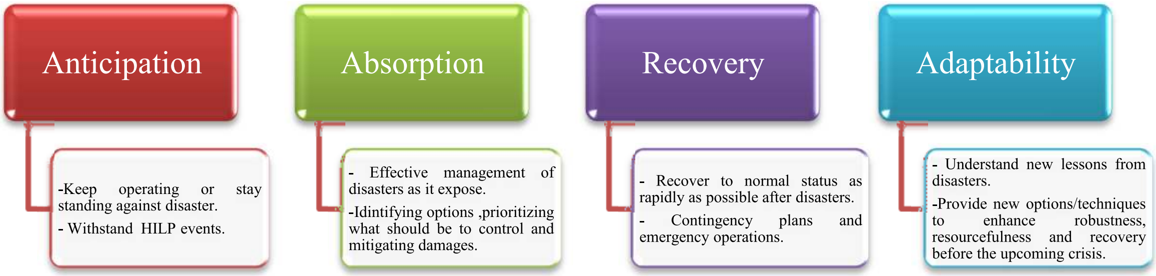

FIGURE 2. The basic characteristics of resilience.

TABLE 1. Synopsis of the general definitions of resilience and their main characteristics.

Author/ Organization	References	Extracted Characteristics of Resilience								
		Tolerance	Resistance	Robustness	Anticipation	Adaptation	Absorption	Recovery	Learning Lessons	Alternative Service
MCEER	[19]	√				√		√		
UKERC	[21]	√						√		√
UK Cabinet Office	[22]				√	√	√	√		
NIAC	[23]			√		√		√	√	
SRC	[24]			√		√				√
IPCC	[25]				√	√	√	√		
PPD-21	[26,27]		√		√	√		√		
UN-ISDR	[28]		√	√				√	√	
Overbye et al.	[29]	√						√		
Keogh et al.	[30]			√				√		
Field et al.	[31]				√		√	√		
Haimes	[32]		√					√		
Willis et al.	[33]			√		√		√		
Aven	[34]	√								√

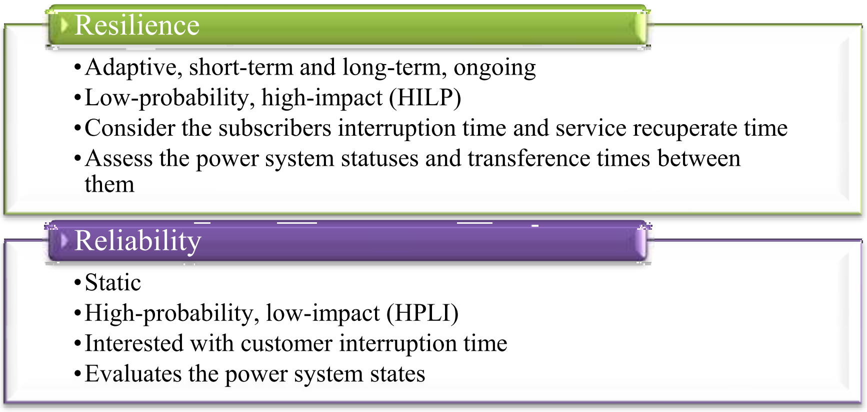

FIGURE 3. A brief comparison between the features of resilience and reliability.

emergencies, which result in impermanent outages. A reliable power system must be able to minimize power interruptions and rapidly recover from blackouts. Otherwise, the disaster, which usually contains blackout, alludes to extreme and quickly varying conditions that may not have been experienced before. The disaster can cause many parts of the power system to fail, often large, relying on the magnitude of the disaster. Thus, the system that can keep up a high degree of execution under any circumstance ought to be reliable to the most widely recognized power outages, yet in addition resilient with low probability disasters [40]. According to the above-mentioned characteristics, resilience is a function of time; therefore, it can be split into two-terms as the following:

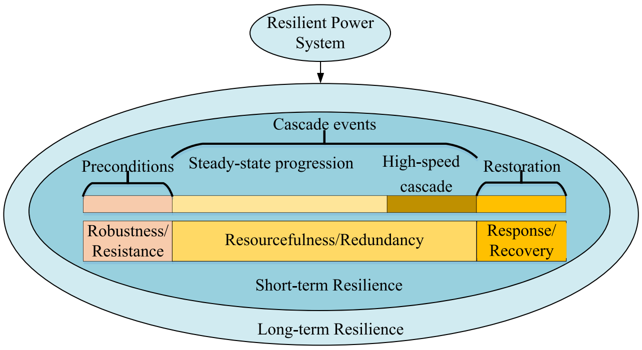

FIGURE 4. Blackout scheme for short/long-term power system resilience.

A. POWER SYSTEMS' SHORT-TERM AND LONG-TERM RESILIENCE FRAMEWORKS

Power systems resilience is illustrated as a function of time by using the blackout scheme appeared in Fig.4 [41]. The short-term resilience alludes to the characteristics that a system should have prior, during, and after events (i.e. robustness/resistance, resourcefulness/redundancy, and recovery). The adequacy of preventive and restorative measures strongly relies upon the capacity of framework administrators to understand and perceive the data and information received correctly, identify the issue and needs, recognize accessible assets, and then set the most proper actions to restore the system to the pre-condition situation. The short-term resilience varies through disturbance, contingent upon its capacity to adapt effectively and quickly to advanced system conditions or to gradually deteriorate during electrical disturbances.

The long-term resilience indicates the system's ability to adapt to changing circumstances and new menaces. In power systems, adaptability is accomplished overextended danger and reliability investigations, inclusive prospect future situations, to specify key threats to the stability of the energy system. Actions are then utilized while deemed important to enhance the system's flexibility for both expected and unexpected events.

B. RESILIENCE CURVE-RELATED DISTURBANCE EVENTS

The essence of resilience is integrated through resilience curves. As with the definition of resilience, there is no unanimity on the representation of the resilience curve. Resilience curves include key features of power systems to deal with external disturbances. Figure 5 shows the recent curves of resilience found in the literature. Figure 5 (a) illustrates the conceptual resilience curve in which resilience is further classified into operational resilience and infrastructural resilience [42]. The operational resilience consists of four cases associated with schedules of the power system during a disturbance. The first case, entitled "resilient state", describes the operation of the power system before the disturbance occurs. The main features of this case are robustness/resistance of the system to resist the first shock. After that, the system enters a "state of post-event degraded" after being disturbed. Here, the main features that provide operational flexibility are adapting to evolving conditions of resourcefulness, redundancy, and self-organization to help minimize the effect of the event. After that, the system enters the "state of restorative" where the system must show a quick response to ensure maximum recovery to reach the resilient state again as soon as possible. The system then enters the "post-restoration state" where the resilience level likely to be high as the pre-event state depending on the post-event robustness and resistance features after the event, which means that the system may or may not recover its full

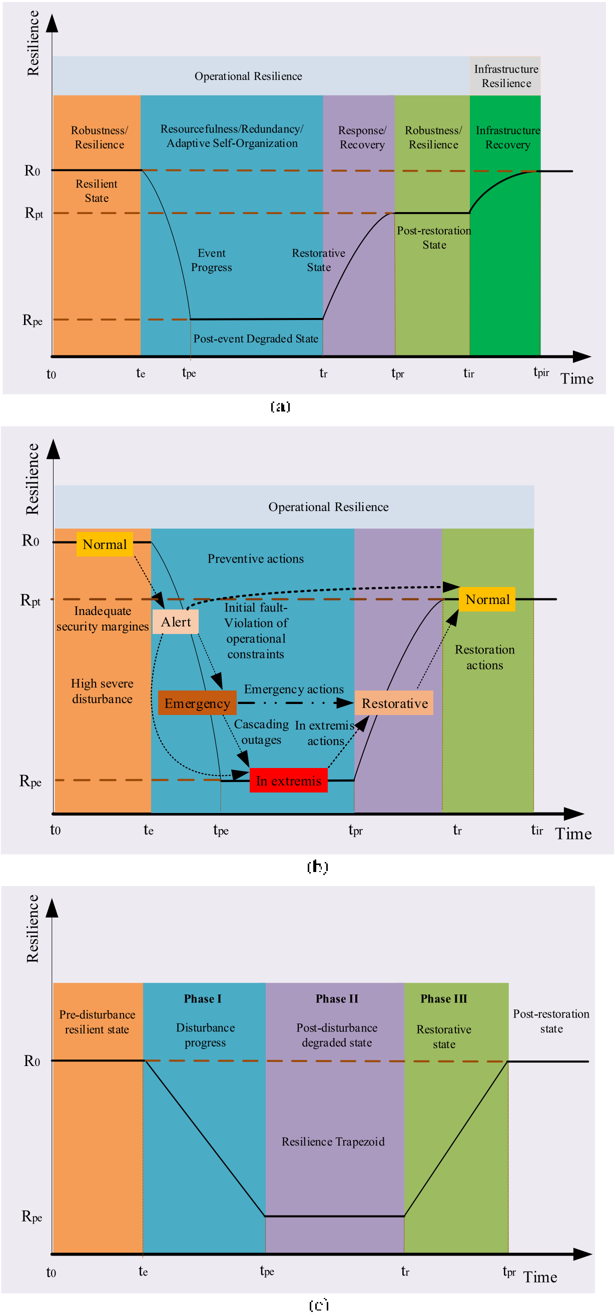

FIGURE 5. Resilience curve-related disturbance events.

operational capacity. Infrastructure resilience deals with the degree to which the infrastructure is recovered based on the disturbance seriousness and the ability of resilience features. Furthermore, it is a remarkable fact that some resilience measures may enhance the operating resilience of the system but weaken the system's resilience from an infrastructure standpoint.

Another recent representation of the resilience curve was provided in [43] as shown in Fig.5 (b). The authors compared the traditional and resilient system response with the subversive event. The pre-event state helps to prepare the system for the disruptive event by identifying the spatial and temporal aspects of the event through a decision support system and advanced weather forecasting. In the state of deterioration, the system tries to resist and absorb the event, and then enters the system in case of post-event deterioration where the system adapts and responds to losses incurred by the event. Thus, the system enters the restoration state where the system attempts to recover to its pre-event state, and finally, the system enters the normal operating state after the retrieval to its pre-event state. The perception of resilience curves was further improved in [44] where the authors proposed a trapezoidal multilevel resilience as shown in Fig.5(c). The pre-disturbance resilience of the system can be improved through accurate time and location prediction of the disruptive event. The first phase of the trapezoid displays the performance of the system where the system faces the event; emergency or corrective actions that have been adopted during this phase can help to mitigate the event effect on the system. During the second phase, the system is in a state of post-disturbance deterioration and system recovery will begin. After the degraded phase, the system enters the recovery stage as the system fully recovers to the pre-disturbance level. Finally, in the post-restoration state, the impact of the event on the operation of the system is evaluated and analyzed to prepare adaptive actions to excess the system's resilience to manage similar future events [45].

C. THE SCOPE OF SYSTEM RESILIENCE BASED-EXPOSURE INTENSITY

Extreme weather is difficult to be dominant because of its naturalistic behavior, whereas severe effects can be dominant by managing the exposure and vulnerability of the power system [46]. The intensity of these events is determined by their severity, duration and area affecting them. For example, storms and hurricanes are particularly assessed depending on the existing wind characteristics. The resilience of the power system deals with severe climatic events whose probability is limited but their prospect to introduce enormous and extended effect is high. Thus, the significant effect of normal weather is not the focus of interest in this research. Figure 6 exhibits the range of power system resilience-related exposure intensity [47]. The figure shows the effect of weather, resulting from three elements (i.e. weather intensity, exposure to the power system, and vulnerability of the power system) [48].

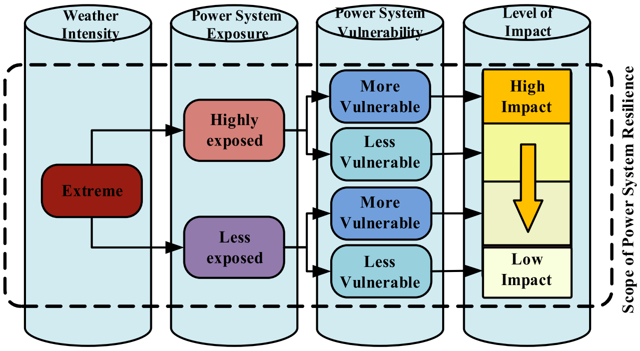

FIGURE 6. The scope of power system resilience based-exposure intensity.

IV. PROACTIVE RESILIENCE OF POWER SYSTEM

The proactive resilience of the power system is defined as the preventive and restorative plans which can be considered to reduce the effect of extreme weather events and prevent cascading failures [49]. The hypothetical and commonsense ramifications of the created models will drive the examination wilderness into a proactive reaction in power systems, while their adaptability will bolster implementation to an assortment of structures in light of a wide scope of extreme weather occasions and naturalistic disasters. In this regard, preventive and restorative strategies that can be connected to alleviate the climate impact are examined in the following sections:

A. PROACTIVE STRATEGIES OF POWER SYSTEMS FOR RESILIENCY ENHANCEMENT TO ADVERSE WEATHER

Most worldwide electrical power systems have realized the necessity to take action to enhance network resilience for HILP events. These actions are primarily aimed at adapting the system, which alludes to actions taken to diminish the effect of future events, and enable the viability which alludes to the capacity to keep up an appropriate function prior, during and after the event. Enhancing the resilience of the power system can be performed through different strategies, which are found in several literatures (i.e. hardening or operational strategies). An appropriate roadmap to improve the resilience of the power system should consolidate both for the better resilient system. In addition, an accurate choice is required to apply one enhancing strategy given budget constraints, resources, time, etc. Therefore, priority should be given to a specific feature of one energy system to implement system resilience strategies.

The defect caused by climate conditions can be impermanent and can be realized rapidly through manual/automatic reclose, which may consume time to recover contingent upon the device harm. Many protection strategies are therefore performed to enhance network resilience in these events, which have been divided into short/long-term plans [41], as detailed in Section III.

The short-term plans allude to the protective and corrective plans connected previously, days or weeks, during and after a severe weather occasion. Upon the metrological data, facilities must effectively utilize the accessible resources to get ready for the upcoming climate occasion. The strategies that can be made incorporate contingency planning, generation dispatch; ensuring black-start abilities and managing with nearest facilities (i.e. a practical case study in [50]). Next to the weather occasion, rapid recuperation is significant. Black-start abilities, appropriate correspondence techniques, recovery and emergency methodologies allow rapid recovery of damaged facilities and separate customers.

On another hand, long-term plans indicate long-term adaptation planning to enhance the network's resilience to cope with adverse climate occasion in the future as shown in Table 2 [9], [51]–[54].

TABLE 2. **The long-term resilience plans.**

Operational Plans
- Events evaluation and executives to assess and prepare for risks arising from it. - Precise assessment of the weather position and intensity - Improved contingency planning and preparedness
Hardening Plans
- Laying wires underground. - Enhance the robustness of the components - Excessive transmission tracks and redirecting it to the least vulnerable areas. - Raising substations and moving parts to regions less inclined to flooding
Smart Plans
- Smart grids, *MGs* and distributed energy resources (DER) - Increase perception and awareness of the situation utilizing developed observation and forecasting tools. - Maintain backup towers and materials.

The effects of short/long-term resilience plans differ through the climate occasion. For instance, improved circumstance awareness can help administrators in disaster management as they are revealed by the use of accessible resources, while operation and auxiliary plans can enhance the system's robustness and resistance to the effect of extreme climate. For example, the authors in [55] proposed a structure for power frameworks planning considering resilience against extraordinary climate occasions. They proposed a set of linear models to measure the effect of extraordinary heat waves and dry season occasions. The outcomes demonstrate that noteworthy improvements as far as load supply during these occasions can be accomplished under the resilient planning framework contrasted with regular planning.

The authors in [42], presented a long-term resilience framework concentrate on vulnerability/adaptation investigation, identification and prioritization of resilience improvement methodologies, cost/advantage examination, and the application of improvement methodologies. The vulnerability investigation includes three states, which are resilient, degraded, and restorative. Cost/advantage examination has been incorporated to assort enhancement strategies depend on resilience or cost-efficiency. In this manner, the eventual resolution relied on the owner's choice.

The resilience enhancement actions are decided based on the significance of each action and its contribution to improvement. These may allude to operational and enhancement procedures that have been examined in the following sections. Nevertheless, some of these actions are further efficient or cost-effective than others. Hence, the cost examination would assist to gain insight into the advantages of applying each plan to the cost of implementing the plan. Following this analysis, resilience procedures can be categorized and carried out upon their resilience and cost-effectiveness indicators, which will help establish an integrated power infrastructure. These objectives can be achieved through resilience engineering to enhance network resilience prior and during the event, and disturbance management to improve response after the event. These objectives can be achieved primarily utilizing hardening and operational procedures. Hardening procedures are referred to as measures to strengthen infrastructure to make the system minimal vulnerable to extreme events. Hardening procedures usually require large amount of investment, and in many cases one hardening procedure can be only effective to a specific type of event. On the other hand, operational procedures indicate to ''smart'' control measures applied to give resources control and assets to manage a crisis circumstance as it happens. In particular, the objective of operational procedures is to push the system to ''bend'' not to ''break'' against disaster. The strategies to improve the resilience of the energy system serve two purposes: to reduce the immediate impact of the severe weather event and to quickly iterate the function of the power system to its stable state. It tends to be classified into two major sets, includes enhancing the physical hardiness of the power system and the operating power system capacity. In general, the physical hardiness of the power system is used to reduce the effect magnitude, and the improvement of the capability of the power system operation is applied to minimize recovery time [56]. Table 3 presents a synopsis of former studies on the enhancement strategies of power system resilience. In this paper, we concentrate on the operational capability strategies for power system resilience enhancement. In many existing works of introducing coordination mechanisms for dispatchable and non-dispatchable energy sources, *MGs* and DERs are believed to enable delaying system upgrade or capacity increment if they are strategically deployed for several specific operations tasks [57]–[72]. However, by considering the additional resilience requirement and general advantages of satisfying all the operation goals, direct upgrading the operational capability of system main components is still the major maneuver to guarantee long-term performance, especially when facing the extreme event challenges. Besides depending on island operation, emergency generator and mobile substations, enhancing the bulk operational capacity of the main grid is still admitted as a premier solution or fundamental support for other coordination mechanisms.

TABLE 3. Classification of strategies of enhancement power system resilience.

Power system capability	Strategies	References
Operational capability	Smart grid, *MGs* and DER Power system monitoring system Management of spare parts and repair kits Organize and design upgrade standards Emergency generator and mobile substations	[57-72] [60, 73-76] [77-83] [59, 84-86] [84, 87-92]
Physical hardiness	Underground selective Elevated substation and water barrier Physical upgrade and revitalization Transfer sub-station and forwarding lines Vegetation management	[93-99] [62, 89, 91, 100-104] [84, 89, 105-112] [84,113-116] [59, 84, 88, 89, 91,95, 96, 102,104, 117-122]

B. MACHINE LEARNING-BASED PROACTIVE STRATEGIES OF POWER SYSTEMS FOR RESILIENCY ENHANCEMENT

The proactive strategies of power systems for resiliency enhancement usually depend on comprehensive monitoring and accurate malicious operation condition detection of the system status with an automatic and autonomous implementation manner. Nowadays, the abundant monitoring data collected from various power network edges and deployed monitoring equipment (e.g., SCADA, PMU) enables better awareness of the potential proactive actions [123], with or without human expert knowledge, prepared hour-ahead or day-ahead before the actual occurrence of extreme events. By fully leveraging these system status data and critical infrastructure resources (e.g., recloser, energy storage system, and mobile compensator) availability information, machine learning-based or aided approaches can significantly increase the efficiency and fast response of the decision-making process at the proactive stage for power system resiliency enhancement [124]. Additionally, machine learning-based methods are able to overcome some hurdles that are difficult for other methods (e.g., optimization-based, rule-based) of implementing proactive strategies. For example, the consideration for HILP events in resiliency enhancement often implies a low sampling efficiency in generating a considerate number of scenario samples feeding to a stochastic optimization framework. Thus, only with very a few extreme event data samples, the optimization constraints are hardly characterizing the range of suitable proactive or preventative action space. Even using ambiguity set in robust optimization, without approximation for a certain probability distribution function, the constraint still suffers the problem of too sparse ambiguity set that is rarely supportive and robust for incoming out-of-sample testing performance. However, recent advances in machine learning techniques, like generative adversarial network (GAN), can effectively solve similar problems by generating at least superficially authentic data samples that keep similar probabilistic structure. The pioneer work in [125] tried using fully data-driven approaches depend on generative adversarial networks and PMU data for power system dynamic security appreciation. It could be utilized to deal with the pre-fault low-probability high-impact critical security condition estimation in proactive power system even with incomplete data measurements. A similar strategy in [126] also uses generative adversarial network for model-free renewable scenario generation and can prepare these renewable energy resources to back up the power system operation facing extreme harmful events. Furthermore, due to the feedforward nature of neural networks, scenarios or new data samples are actually produced considerably efficiently without the need for sophisticated sampling mechanisms. By using these data augmentation technologies, the real-world measurements and observations in rare events could be resampled, enabling occurrence features captured for generating similar repetitions. Meanwhile, these machine learning-based methods are also partially using software simulators to generate artificial event triggers that consist of no real-world measurement information at all. The extreme event simulation using pure artificial signal aims to increase HILP event sampling efficiency as much as possible and prepare for the pre-trained model. Additionally, through the machine learning-based and simulation-aided methods in an experimental environment, the effectiveness of the resilience enhancement strategy could be preliminarily validated to prevent it from observable and easily detected maloperations, such as actions leading to cascading failures.

On the other hand, machine learning-based methods of designing a proactive strategy in resiliency enhancement can provide an online implementation of actuators with offline training. In this way, preventative and proactive solutions can be pre-calculated before the actual occurrence of extreme events. Unlike the optimization-based methods that obtain the intermediate results and final solutions as a whole, which are either based on day/hour-ahead framework or real-time framework (including two-stage framework), machine learning-based methods could sperate the training process of intermediate results and problem-solving process in different time horizons. For example, in the work [127], a deep reinforcement learning (DRL) and simulation-based framework with a pre-calculated neural network structure are used to deal with an adaptive power system emergency control problem. The reinforcement learning module, as a problem-solving engine, automatically determines its Q-network weight parameters via repeatedly simulated samples before the actual decision-making of a proactive strategy. A similar machine learning-based and a simulation-aided idea can also be found in work [128], which has a vulnerability analysis of a smart grid against extremely frequent cyber-attacks. The training episodes of Q-learning algorithm are repeatedly generated via an embedded simulator for mimicking cascading outages. The work in [76] leverages logistical regression, utilizing a second-order function and proper parameter fitting, to estimate the potential outage of power grid parts in response to an imminent hurricane; the work in [129] proposed a three-step sequential method, utilizing posterior probability model and twin support vector machine, in identifying proactive load curtailment strategy prior to hurricane occurrence. As a summary, the comparison between optimization-based and machine learning-based proactive strategies of power systems for resiliency enhancement is presented in Table 4.

TABLE 4. Comparison between optimization-based and machine learning-based methods for proactive strategies design.

	Optimized-based Methods	**Machine learning-based Methods**
Modeling	Usually model-based and need a physical model description for characterizing the resilient power system operation features.	Usually model-free and data-driven with a focus on the input-output relationship of a proactive strategy.
Sample efficiency	Make use of all the available data samples of extreme events and system characteristics at the current time interval.	Make use of available data samples or historical data and can use data augmentation techniques (e.g., GAN) to increase sample efficiency of extreme event.
Decision-making	Based on day/hour-ahead framework or real-time framework (including two-stage framework) and decision-making at the same time horizon.	Able to sperate the training process of intermediate results and problem-solving processes in different time horizons.
Accuracy	Accurate analytical solution results with a clear interpretation of proactive strategy scenarios.	Usually non-analytical and non-deterministic solution results with dependency on sample data quality.
Implementation	Might have high computational complexity and time if involving integer variables representing switching actions in a proactive strategy.	Could have a good pre-training model to reduce the calculation time in final decision-making while implemented for proactive strategy.

V. ENHANCEMENT OF POWER SYSTEM OPERATIONAL CAPABILITY

The basic rule of the operational capacity of a power system is to rapidly restore system functions. There are two efficient approaches to accomplish this objective. One includes giving transitory support during power outages using an emergency power source or reconfiguring the power system configuration. The other includes the mend and renovation of failed components of the power system. Thus, the viability of asset assembly and the arrangement of rebuilding have turned into the way to quick recuperation [130]. The assets incorporate standby power supplies, backup parts, and fix units. Furthermore, enhancing the operational power of the system relies upon the execution of the operating algorithm, control of the system arrangements and automatic self-healing mechanisms. An effective strategy to enhance the resilience of an energy system is the utilization of *MG* as the following:

A. MICROGRIDS AND DISTRIBUTED ENERGY RESOURCES

The *MG* is basically characterized as a sub-set of the grid (normally at low/medium voltage levels) which can be islanded or yet gives all or part of its customers during crises, in this manner enhancing the system's intrinsic resilience. The main objective and properties are to guarantee moderate energy reliability and security for subscribers. The advantages extended to the community incorporate low CO_2 emissions and low pressure on the system facilities [131]. The *MG* requires intelligent technologies to continue supplying power to customers in island mode. For example, when connecting to the main grid, *MGs* depend on a combination of generation, depending on the measurement to be improved (eg, cost, greenhouse gases, and reliability). Many projects around the world aim to develop *MGs*, which are seen as one of the major promising procedures to improve the resilience of future power systems during emergencies.

The development of the *MGs* has acquired immense advantages to the network in relevance to severe weather events, and their utilization was relied upon to enhance network resilience [58], [61]–[63]. Moreover, it can give an alternative of self-supply the around zone during emergencies [65], [69]. With smart grids (*SGs*) and responsive *MGs* the mitigation of extreme events impacts can be faster, effective and *MGs* with a protective island can maximize system restoration [66]. This strategy maximizes system capacity through the distribution of energy to customers. In addition, the effects of power components faults can be diminished by utilizing DER and *MGs* [132]. Meanwhile, the utilization of plug-in electric vehicles through *SGs* can also enhance the system's resilience during extreme weather events [60]. Despite the utilization of *MGs* and DER can enhance the system resilience, further studies and procedures are needed to decide their optimal configuration. For instance, Campbell [59] has tried numerous endeavors to decrease storm-related outages, incorporating the execution of *SGs* and DER. In [67], the authors presented an approach for expanding the power system to decide a more resilient system configuration in development arranging. The ideal arrangement was gotten by limiting the general expense and hazard level of unsuitable reliability. The level of unsuitable reliability risk has dictated by decreasing the load. The authors in [71] displayed an ideal situation, in addition to the optimal size of DER as PV output and storage unit size to improve power system resilience. Nevertheless, the target of this situation was to diminish the non-supply limit by thinking about the venture and operational costs of the DER, achieve the demand, and the non-black-start generation units. The same methodology has been considered by Zari *et al.* [72] to identify the ideal switches situation to enhance power system resilience versus cyclones. By applying the vulnerability curve, the model was utilized to obtain the effects of the cyclone. The ideal situation of switches was controlled by limiting the intermittent load for every design of the time step, the ordinary and harmed feeders, and the load positions. In [70] the authors presented the control of network topology to improve power system resilience through forecasting data and executing a hazard executive's procedure. This procedure can be utilized to set up the moderation plan when a troublesome occasion is experienced by controlling the Transmission Line Switching (TLS) before the occasion. The authors in [68] introduced a scheduling framework for *MGs* to against the advent floods. This framework incorporates an investigation on vulnerability, most pessimistic scenario examination and proactive scheduling. In [57], the authors introduced the proactive management of the power system through a Markov procedure to limit the present and future expenses brought about by the harms. To start with, the fragility curve of the system parts was planned explicitly for various kinds of extreme weather conditions, and to ascertain the likelihood of system parts damage. The present and future conditions of the system are defined because of the corrupted component and utilized to decide system operation. Consequently, the decision to operate the system was adopted at its present and future cost. A real system has been utilized to verify this procedure, and the outcomes showed that the introduced proactive procedure could limit the load interruptions related to extreme events. The following sections outline *MGs* related actions to enhance resiliency:

1) PROACTIVE MANAGEMENT OF *MGs* FOR RESILIENCY ENHANCEMENT

The system resilience is the capability to deteriorate safely after disturbance, to change its configuration in a graceful manner, and to quickly recuperate after disturbances [133], [134]. These features accomplished by means of *MGs*. The *MG* is a combination of DER and loads associated with a system of feeder units situated at the same point [135], [136]. Furthermore, *MGs* can be operating in grid-connected or islanded modes [137]. Over the grid-connected mode, the power interchange among the main grid and the *MG* can be either positive or negative. But, in the case of major grid interruption, the *MG* islands thus provide part of their loads, depending on accessible assets inside the *MG* [138]. The *MG* deployment with islanding and self-supply capability can enhance the resilience of the power system to adapt to weather conditions significantly. With this regard, feasible ways are required to operationalize and handle *MG* to optimize resource control and minimize risks in the face of such disturbances.

The gainful impacts of *MGs* on the resilience of the power system were widely recognized in the literature. However, a limited number of numerical strategies have been presented in this issue. For example, in [139], a two-stage stochastic programming procedure is introduced to optimize the *MG* schedule, where the islanding occasion effect is designed through a stochastic programming model. The authors in [140] proposed a resilient planning layout for the distribution network to facilitate the hardening and DER asset designation with a view to limit system damages. In [141] the authors introduced developed *MG* load management functions to optimize *MG* storage, electric vehicles integration, and load response, to enhance *MG* resilience after island occasions.

MGs have the ability to mitigate the adverse effects of HILP events. However, it is difficult to precisely evaluate the probability of these events [56]. In fact, it is very difficult to get accurate appreciations of future HILP prospects. However, in spite of the prospect apportionment of HILP events is not easily available, prediction models can be utilized to deal with these events. As mentioned previously, the resilience of the power system has basically three phases: preparedness, mitigation and restoration [133]. During the prepare phase, the *MG* administrators expect to expand the degree of preparedness via proactive management procedures. In fact, at this stage, the *MG* administrators expect to absorb and anticipate potential stuns to moving toward occasion and pick preventative measures to minimize the adverse results of the event. In [142] the authors proposed a robust two-phase proactive scheduling framework for the *MG* to limit the adverse outcomes of the islanding occasions. This framework takes into account various uncertainties and gets the best timeline for moving forward in the *MG*, which is strong against achieving uncertain criteria. The column-generation and constraint algorithm is adapted to tackle the issue proficiently, and the ''uncertainty budget'' is presented to control the maintenance of a vigorous arrangement. The adequacy of the proposed framework is assessed on *MG* using a lot of illustrative contextual analyses. The reproductions results showed that the framework reduces the high cost of load shedding to the detriment of a slight increment in the expense of pre-turbulence planning. The merits of this framework are noticeable while weather conditions occur, and there is a high level of uncertainty. The authors in [143] present a *MG* proactive management approach to deal with the harmful effects of severe windstorms. After getting cautions for the expected windstorm, the approach decides a preservationist schedule of *MG* with the least number of vulnerable branches in administration during the delivery of the total load. The schedule guarantees the *MG* ordinary operation before the windstorm while diminishing the *MG* vulnerability at the beginning of the event. The presented technique benefits from system reconfiguration, rescheduling/backup generation, and voltage regulation. A vulnerability index is determined to estimate the proposed proactive management validation in minimizing the *MG* vulnerability at the beginning of the event.

The strategies to enhance resilience were sorted in the literature as hardening-oriented and operation-oriented strategies [44]. Hardening-oriented strategies are aimed at strengthening components and making systems less vulnerable to HILP occasions. Supporting infrastructures with robust materials and lifting substations are instances of these strategies. However, limited studies were introduced in the literature on the effects of these strategies on power system resilience [144], [145]. The operation-oriented strategies allude to proactive control-based plans considered to make the system able to deal with the undesired situation when it detected. The main objective of operation-oriented strategies is to let the system proactively ''bend,'' rather than ''break,'' against severe events [44]. The rescheduling of generations, voltage regulation, the cautious island, and priority-based load shedding are instances of these strategies Rather than hardening-oriented strategies, the operational-oriented strategies are continuous, proactive, and moderate solutions for a progressively flexible system. A coordinated preventive-corrective structure is introduced in [146] to improve the resilience of the power system to cope with natural disasters. This structure uses situational awareness to enhance resilience and gives effective reactions in preventive and emergency situations as well. Expanding consideration is being paid to the effect of *MGs* in restoring administration and enhancing power system resilience [139], [61], [147]–[153]. The authors in [154] have reviewed the current achievements in preparedness before the severe weather and emphasized the allocation of resources in the distribution systems before a cyclone. Fuel, power banks, and electric transports are dispensed to be utilized in post-cyclone restoration.

2) SEQUENTIAL PROACTIVE OPERATION STRATEGIES

With interruptions and forecasts, many proactive strategies (i.e. preventive) can be implemented prior the extreme weather event for resilience enhancement. Furthermore, careful forecasting of the interruption contributes to the management of preparing and recovery endeavors. To enhance the precision of predictions, a two-dimensional negative regression model has been introduced in [155]. This model is suitable just for a particular service region, since it depends on data with respect to outages brought about by specific hurricanes events. To face this problem, a general model for the entire US coast has been introduced in [156]. To evaluate power interruption time spans of hurricanes, a statistical model is presented in [157]. The authors in [158] propose a mixed-integer stochastic programming framework to measure the worth that chemical facilities can provide to the resilience of the power systems through demand response. In view of the stochastic and sequential properties of events, the prospect effects of events on power system resilience are investigated utilizing sequential Monte Carlo emulations [43]. Meanwhile, to limit adverse effects, the reaction prior the hurricane is designed as a mixed-integer objective function [83]. In addition, the planning of adequate generating units of emergency and black-start sources additionally improves the resilience of the power system before a severe weather-related event occurs. To evaluate black-start capabilities, a GRM algorithm has been introduced in [159]. To give sufficient black-start generation at the appropriate placements, the authors in [160] proposed a model to develop an acquisition plan at the lowest possible cost while ensuring adequate black-start capabilities. In addition, a few procedures, for example, mobile emergency generator [161], conservation arranging [162] and wide-area controls in light of communication interruption [163], [164] can likewise be actualized to upgrade the resilience of the power system prior to a weather event. In [66], a standardized resilience assessment and an improvement strategy, comprising a new defensive islanding approach, are presented. This approach can relieve prospect sequential impacts during extreme weather events. The authors in [165] proposed a new operation and self-healing approach for the distributed generators; dividing them into several *MGs*, in order to enhance their resilience.

After a severe weather event, it is essential and mandatory that system operators rapidly execute system and load recovery strategies. These strategies are not the focus of attention in this study, however it can be found in detail in the literature [166]–[168].

3) OPTIMAL PLACEMENT OF *MG* FOR ENHANCING POWER SYSTEM RESILIENCE

In the context of *MG* placement to enhance resilience of the power system, limited work was founded in the literature. However, in [169], a planning approach has been proposed to integrate DER into *MGs* from a planning viewpoint that is designed as an optimization function with economic, reliability and vulnerability objectives. This function is resolved through multi-agent systems and particle swarm optimization. Nevertheless, this approach is complex and not effective.

In [170] the authors proposed an optimal model for placement the *MG* to enhance the resilience of the power system. The *MGs* size and placement were resolved so as to limit the load shedding prior hurricanes. The potential failure model of the framework parts has been realized to create suitable plans to estimate the effect of hurricanes on framework outages. Furthermore, this model distinguishes the resilient process in emergencies. *MGs* were realized as total and adaptable loads from the framework administrator's point of view, and their reaction was designed according to the framework outages.

4) RESILIENCY-ORIENTED *MG* OPTIMAL SCHEDULING

The *MG* scheduling is performed in a grid and island-connected modes by the MG master controller dependent on the cost and preservation regards. This control controller decides the *MG* association with the fundamental network, the switching choice among the two modes, and the ideal schedule of available assets. The *MG* Islanding's ability speaks to this innovation as a feasible option to solve the system resilience problem and has pulled in extensive consideration lately [171], [172]. Improving resilience is one of the corresponding offers given by the MGs accomplished by encouraging the distribution of DER and islanding [173]. The resilience returns of *MGs* in literature are widely examined.

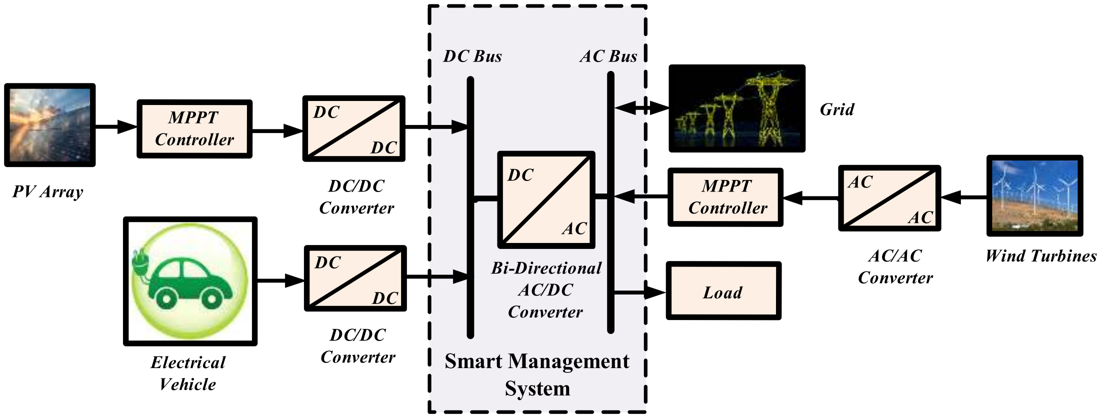

FIGURE 7. A proposed smart system incorporates RES system integrated into the grid.

Nevertheless, the mathematical modeling of ideal *MG* scheduling based-resilience contemplations is limited. The current research on *MG* resilience can be accessed in [174]–[181]. In [174], convenience constraints are realized to guarantee an adequate operating edge in the economic operation of the *MG* and supply the critical demand during initial grid failures. The concept of smart autonomous DER is proposed in [175] for building a resilient, clean and customer-based *MG*, where the load management is used to guarantee load supplying during emergencies. In [176], the *MG* frequency drop control system is proposed to expand the resiliency of *MG* on the traditional distribution network.

In [177] the authors conclude a series of control procedures to be adopted to restore the service of multiple *MG* systems and subsequent islanded mode operation. It was clear that the prospect of the control sequence of procedures permits reducing load recovery times and improving system resilience. The authors in [178] report on ongoing research coordinated at the use of distributed multi-agent structures to accomplish resilient self-healing frameworks via independent management of *MGs*. It is additionally examined that interconnected *MGs* is a practical option for power system resilience. A *MG* to supply a local area situated in a cyclone way is presented in [179]. A control frame and management controller were introduced to settle the system during disturbances.

A study in [180] presents a multi-objective improvement to assess the feasible operation and implementation of DERs in *MGs*. The resilience indicator is characterized as calculating the power of the self-recovering system to natural operation following the unexpected occasion. In [181], the authors proposed a model of resiliency-oriented *MG* scheduling. A central scheduling model in which the main controller collected all the needed information to schedule the *MG* and implement a centralized operation and control process. The presented model guarantees the safe operation of *MG* and is appropriate for applying optimization procedures. The ordinary operation of the grid-integrated *MG*, is facilitated with a resilient operation to enable quick exchanging among the two modes with no load outages. The authors in [182] reviewed microgrids formation and proposed resilience-oriented operating strategies to enhance power system resilience. They summarized that utilizing microgrid as a resiliency resource can help decrease the effects of energy disturbance events and limit the impact of intermittent renewable energy generation on power systems.

B. THE ROLE OF RENEWABLE ENERGY INTEGRATION ON ENHANCING POWER SYSTEM RESILIENCE

Renewable energy sources (RES) incorporate different technologies, such as, wind turbines, solar PV, electric vehicles and energy storage. Conventionally, the interconnection standards necessitate that RES be disconnected from disasters [183]. However, with increasing RES penetration, there is a critical desire to reconsider this issue. A case of this is the view of utilizing RES during the restoration process [184], and another is utilizing RES in resilience to respond to protect frameworks. Notwithstanding, given that a few RES (eg, wind and solar) are regularly fickle and hard to anticipate precisely, managing vulnerability might be a major issue in using RES to enhance the system's resilience to withstand disasters. In addition, the difficulty in managing the vulnerability can be extraordinary as the profound penetration of the RES is as of now in progress. Likewise, as uncovered in an ongoing overview [185], numerous facilities notice cost requirements and financial related imperatives as an impediment to disavowing RES. Subsequently, making RES economical can be significant in advancing the use of these sources in enhancing power system resilience. Moreover, we ought to know about the potential antagonistic effects of incorporating RES into the power system. Numerous ideas have been introduced to integrate RES into power systems and to minimize the cost objective function [186]. In this regard, a hybrid RES system integrated into the grid and its smart operation is proposed in this paper in order to enhance the system resilience. The system incorporates wind turbines, solar PV, and electrical vehicle integrated to the grid through AC/DC bus as shown in Fig.7. A smart management system to monitoring and control the entire system is planned so as to guarantee an adequate balance between the generated and demanded energy. The system employs an intelligent optimization algorithm (IOA) to manage the control, the load data, and the metrological data of the RES (e.g. wind speed, radiation, temperature). The main objective of the IOA is to manage the proposed system to fulfill the minimum total cost (*TC*) and maintain the system energy balance as shown in the accompanying constraints:

$$MinTC = Min\sum_{t=1}^{T} FC(C_{g,t}(t)P_{g,t}) \quad (1)$$

$$P_{w,t}(t) + P_{pv,t}(t) \pm P_{g,t}(t) \pm P_{e,t}(t) = P_{l,t}(t) \quad (2)$$

Where, FC is the cost function of the borrowed energy from the grid, $P_{g,t}(t)$ is the power transfer between the system and the grid, and $C_{g,t}$ is the price/kWh per hour, t through the life time of the system, T. $P_{w,t}(t)$, $P_{pv,t}(t)$ are the wind and PV power, respectively. $P_{g,t}(t)$ is the transfer power between the electrical vehicle and the system, and $P_{l,t}(t)$ is the load demand. Getting minimum cost of the proposed system insures its economical operation with in turn enhance the system resiliency.

VI. CONCLUSION, RECOMMENDATIONS AND FUTURE RESEARCH TREND

A. CONCLUSION

Building a reliable power infrastructure for recognized and feasible threats, yet in addition resilient for HILP events, is a major challenge. In order to achieve this dilemma, we first need a deep perception of the meaning of resilience. Resilience is certainly not a static concept, but a dynamic and a continuous method to adapt the frameworks and operations for the superior preparation for unexpected exterior shocks. Since the face of HILP events remains a major challenge; the resilient power system ought to be robust and flexible to operate, but must also have the ability to adapt to schedule, encourage and execute plans to prepare for the same or novel occasions in the future. This is viewed as a major challenge, where building a combined reliable and resilient system isn't an easy issue. Since the electrical power frameworks are planned customarily to be reliable during ordinary conditions and anomalous yet predictable crises. But, they were not intended to adapt the HILP occasions. The most evident methodology is to assemble a larger and more powerful energy system; however, what is the viability of this methodology as far as strength and cost?. As far as strength more thoughts can help with the idea of reliability to address this issue. As far as cost, the best arrangement can be to utilize smart operational measures.

This paper introduces a recent review of the studies on the proactive resilience of a power system that spotlights on specialized issues from the perspective of system engineering. It provides definitions, frameworks and enhancement strategies for power system resilience. The study in this paper focuses on the system resilience against extreme weather events. A system resilience framework is provided to present a generic platform for understanding the topics in the investigation of the resilience of the power system. Many strategies are categorized and introduced to enhance the power system resilience based on the operational capacity of the system. Among them, the *MGs* and their diverse functions are introduced as one of the best enhancement strategies for power system resilience.

B. RECOMMENDATIONS

Upon on the review of the literature of power systems resilience, the following recommendations are presented for future research:

- The analysis shows that the definition of power system resilience and framework needs to be standardized.
- Increased awareness of the importance and features of enhancing the resilience of power systems through a series of research and workshops.
- View the advantages and economic benefits that can be gained by enhancing the resilience of power systems.
- Presenting realistic case studies that include operational aspects of improving the resilience of power systems and implications.
- A sophisticated and intelligent solution covering all operational aspects is required to represent the proactive resilience of power systems.
- A more realistic modeling is required for *MGs* proactive operation and islanding.
- HILP other than hurricanes should be developed with a more realistic consideration of interruptions.

C. FUTURE RESEARCH TREND

In spite of this paper provides an exhaustive review on power system proactive resilience, however, a few points haven't realized and should be considered in the future, which are as follows:

- Present a recent review of the current research on procedures to estimate the proactive resilience of the power system and describe some quantitative indicators. These indicators can be utilized to estimate the resilience of the power system, to compare one system with other systems, and determine the actions to be taken.
- The modeling studies of enhancement strategies are limited. Hence, the evolution of strategies models and the belonged parameters are needed to estimate the benefits of these strategies on power system resilience.
- A comparative study of enhancement strategies of power system resilience is vital. This study should comprise economic considerations and participants' views. The outcomes of this study are important to set the best strategy to be executed on the system.
- A multi-event evaluation must be conducted to ensure that the enhancement strategy for a single severe weather event does not result in a degradation of the system's capacity for another severe weather event.
- Further intelligent plans for the enhancement of power system resilience, such as renewable energy integration, load management, storage optimization, and protection tools, have to be considered in future studies. Then the

economic benefits of executing these plans have to be compared to decide the best one among them.

- An effective optimized framework for the smart operation and islanding of MGs has to be introduced.
- Some proof-of-concepts study with real-world measurement data should be implemented in a field experimental environment to showcase the operation logic and validation of proactive resilience enhancement actions. The simulated extreme event triggers could be generated in an isolated sandbox via the hardware-in-the-loop deployment with reasonable computational resources.

REFERENCES

[1] *Arizona-Southern California Outages on September 8, 2011: Causes and Recommendations*, Federal Energy Regulatory Commission, FERC and NERC Staff, Washington, DC, USA, Apr. 2012.

[2] K. Gordon and M. Dion, "Protection of Critical Infrastructure and the role of investment policies relating to national security," Investment Divis., Directorate Financial Enterprise Affairs, Econ. Co-Operation Develop., Paris, France, Tech. Rep. 75116, 2008.

[3] R. Berg, *Tropical Cyclone Report: Hurricane Ike (AL092008), 1-14 September 2008*, Nat. Hurricane Center, Miami, FL, USA, Tech. Rep. AL092008, 2009.

[4] A. Hu, W. Xie, N. Li, X. Xu, Z. Ji, and J. Wu, "Analyzing regional economic impact and resilience: A case study on electricity outages caused by the 2008 snowstorms in southern China," *Natural Hazards*, vol. 70, no. 2, pp. 1019–1030, 2014.

[5] J. Croke, I. T. C. Reinfelds, and E. Roper, "Macrochannels and their significance for flood-risk minimisation: Examples from southeast Queensland and New South Wales, Australia," *Stochastic Environ. Res. Risk Assessment*, vol. 28, no. 1, pp. 99–112, 2014.

[6] R. Ishihara, "Formation and development of 'disaster resilience theory' in Japan," in *Depopulation, Deindustrialisation and Disasters*. Cham, Switzerland: Palgrave Macmillan, 2019, pp. 253–273.

[7] J. C. Aerts, W. W. Botzen, K. Emanuel, N. Lin, M. de Moel, and E. O. Michel-Kerjan, "Evaluating flood resilience strategies for coastal megacities," *Science*, vol. 344, no. 6183, pp. 473–475, 2014.

[8] H. Jia and D. Pan, "Tornado disaster impacts and management: Learning from the 2016 tornado catastrophe in Jiangsu Province, China," *Natural Hazards*, vol. 89, no. 1, pp. 457–471, 2017.

[9] Executive Office of the President, "Economic benefits of increasing electric grid resilience to weather outages," The Council, Council Econ. Advisers, Washington, DC, USA, Tech. Rep., 2013.

[10] P. Hines, J. Apt, and S. Talukdar, "Large blackouts in North America: Historical trends and policy implications," *Energy Policy*, vol. 37, no. 12, pp. 5249–5259, Dec. 2009.

[11] D. M. Ward, "The effect of weather on grid systems and the reliability of electricity supply," *Climatic Change*, vol. 121, no. 1, pp. 103–113, 2013.

[12] European Network of Transmission System Operators for Electricity, "Nordic grid disturbance statistics," ENTSO-E, Tech. Rep., 2012, pp. 1–92.

[13] G. Strbac, N. Hatziargyriou, J. P. Lopes, C. Moreira, A. Dimeas, and D. Papadaskalopoulos, "Microgrids: Enhancing the resilience of the European megagrid," *IEEE Power Energy Mag.*, vol. 13, no. 3, pp. 35–43, May/Jun. 2015.

[14] Y. Li, K. Xie, L. Wang, and Y. Xiang, "Exploiting network topology optimization and demand side management to improve bulk power system resilience under windstorms," *Elect. Power Syst. Res.*, vol. 171, pp. 127–140, Jun. 2019.

[15] S. K. Huang, M. K. Lindell, and C. S. Prater, "Who leaves and who stays? A review and statistical meta-analysis of hurricane evacuation studies," *Environ. Behav.*, vol. 48, no. 8, pp. 991–1029, May 2016.

[16] C. S. Holling, "Resilience and stability of ecological systems," *Annu. Rev. Ecol. Syst.*, vol. 4, no. 1, pp. 1–23, 1973.

[17] J. J. Walker and M. K. Cooper, "Resilience," in *Companion to Environmental Studies*, vol. 90, no. 94. Evanston, IL, USA: Routledge, 2018, pp. 90–94.

[18] H. Zhou, J. Wan, and H. Jia, "Resilience to natural hazards: A geographic perspective," *Natural Hazards*, vol. 53, no. 1, pp. 21–41, 2010.

[19] A. Filiatrault, "Multidisciplinary center for earthquake engineering research (MCEER)," MCEER, New York, NY, USA, Tech. Rep. MCEER-10-0010, 2014.

[20] A. M. Madni and S. Jackson, "Towards a conceptual framework for resilience engineering," *IEEE Syst. J.*, vol. 3, no. 2, pp. 181–191, Jun. 2009.

[21] M. Chaudry, P. Ekins, K. Ramachandran, A. Shakoor, J. Skea, G. Strbac, X. Wang, and J. Whitaker, "Building a resilient UK energy system," Tech. Rep., 2011.

[22] *Keeping the Country Running: Natural Hazards and Infrastructure*, Cabinet Office, London, U.K., 2011.

[23] A. R. Berkeley, M. Wallace, and C. Coo, "A framework for establishing critical infrastructure resilience goals," Nat. Infrastruct. Advisory Council, Final Rep., 2010.

[24] *Arctic Resilience Report*, Stockholm Environ. Inst. Stockholm Resilience Centre, Arctic Council, Tromsø, Norway, 2016.

[25] T. Stoerk, G. Wagner, and R. E. Ward, "Policy brief-recommendations for improving the treatment of risk and uncertainty in economic estimates of climate impacts in the sixth intergovernmental panel on climate change assessment report," *Rev. Environ. Econ. Policy*, vol. 12, no. 2, pp. 371–376, 2018.

[26] C. D. F. Rogers, C. J. Bouch, S. Williams, A. R. G. Barber, C. J. Baker, J. R. Bryson, D. N. Chapman, L. Chapman, J. Coaffee, I. Jefferson, and A. D. Quinn, "Resistance and resilience—Paradigms for critical local infrastructure," *Proc. Inst. Civil Eng.*, vol. 165, no. 2, p. 73, 2012.

[27] U.S. President, "Presidential policy directive—Critical infrastructure security and resilience," Tech. Rep. PPD-21, 2013.

[28] U. Unisdr, "Hyogo framework for action 2005-2015: Building the resilience of nations and communities to disasters," in *Proc. Extract Final Report World Conf. Disaster Reduction (A/CONF.)*, vol. 380. Geneva, Switzerland: The United Nations International Strategy for Disaster Reduction, 2005.

[29] T. J. Overbye, V. Vittal, and I. Dobson, *Engineering Resilient Cyber-Physical Systems*. Madison, WI, USA: PSERC Publication, 2012, pp. 12–16.

[30] M. Keogh and C. Cody, "Resilience in regulated utilities," Nat. Assoc. Regulatory Utility Commissioners, Washington, DC, USA, Tech. Rep., Nov. 2013.

[31] C. B. Field, V. Barros, T. F. Stocker, and Q. Dahe, Eds., *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge, U.K.: Cambridge Univ. Press, 2012.

[32] Y. Y. Haimes, "On the definition of resilience in systems," *Risk Anal. Int. J.*, vol. 29, no. 4, pp. 498–501, 2018.

[33] H. H. Willis and K. Loa, *Measuring the Resilience of Energy Distribution Systems*. Santa Monica, CA, USA: RAND Corporation, 2015.

[34] T. Aven, "On some recent definitions and analysis frameworks for risk, vulnerability, and resilience," *Risk Anal., Int. J.*, vol. 31, no. 4, pp. 515–522, 2011.

[35] X. Zhang and C. K. Tse, "Assessment of robustness of power systems from a network perspective," *IEEE Trans. Emerg. Sel. Topics Circuits Syst.*, vol. 5, no. 3, pp. 456–464, Sep. 2015.

[36] B. Hu, K. Xie, and H.-M. Tai, "Inverse problem of power system reliability evaluation: Analytical model and solution method," *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6569–6578, May 2018.

[37] M. Vaiman, R. Quint, A. Silverstein, M. Papic, D. Kosterev, N. Leitschuh, A. Faris, S. Yang, B. Blevins, S. Rajagopalan, P. Gravois, O. Ciniglio, S. Maslennikov, E. Litvinov, X. Luo, and P. Etingov, "Using synchrophasors to improve bulk power system reliability in North America," in *Proc. IEEE Power Energy Soc. General Meeting (PESGM)*, Aug. 2018, pp. 1–5.

[38] 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, Apr. 2019.

[39] 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.

[40] D. Helbing, H. Ammoser, and C. Kühnert, "Disasters as extreme events and the importance of network interactions for disaster response management," in *Extreme Events in Nature and Society*. Berlin, Germany: Springer, 2006, pp. 319–348.

[41] W. Lu, Y. Besanger, É. Zamaï, and D. Radu, "Blackouts: Description, analysis and classification," in *Proc. WSEAS Int. Conf. Power Syst.*, Sep. 2006, p. 14.

[42] 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.

[43] 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.

[44] M. Panteli, D. N. Trakas, P. Mancarella, and N. D. Hatziargyriou, "Power systems resilience assessment: Hardening and smart operational enhancement strategies," *Proc. IEEE*, vol. 105, no. 7, pp. 1202–1213, Jul. 2017.

[45] Y. P. Fang and E. Zio, "An adaptive robust framework for the optimization of the resilience of interdependent infrastructures under natural hazards," *Eur. J. Oper. Res.*, vol. 276, no. 3, pp. 1119–1136, 2019.

[46] A. Ka mierczak and G. Cavan, "Surface water flooding risk to urban communities: Analysis of vulnerability, hazard and exposure," *Landscape Urban Planning*, vol. 103, no. 2, pp. 185–197, 2011.

[47] P. Peduzzi, H. Dao, C. Herold, and F. Mouton, "Assessing global exposure and vulnerability towards natural hazards: The disaster risk index," *Natural Hazards Earth Syst. Sci.*, vol. 9, no. 4, pp. 1149–1159, 2009.

[48] A. Satta, M. Snoussi, M. Puddu, L. Flayou, and R. Hout, "An index-based method to assess risks of climate-related hazards in coastal zones: The case of Tetouan," *Estuarine, Coastal Shelf Sci.*, vol. 175, pp. 93–105, Jun. 2016.

[49] 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, Feb. 2015.

[50] *Winter Outlook 2013/14*, National Grid ESO, London, U.K., Oct. 2013.

[51] M. M. Dalton and P. W. Mote, *Climate Change in the Northwest*. Washington, DC, USA: Island Press, 2013.

[52] Energy Networks Association, "Electricity networks climate change adaptation report," Tech. Rep. 1, 2011.

[53] T. Overbye, J. Cardell, I. J. W. Dobson, M. Kezunovic, P. K. Sen, and D. Tylavsky, "The electric power industry and climate change: Power systems research possibilities," Power Syst. Eng. Res. Center, Madison, WI, USA, White Paper 07–16, 2007.

[54] P. C. Johnston, "Climate risk and adaptation in the electric power sector," Asian Develop. Bank, Mandaluyong, Philippines, Tech. Rep., 2012.

[55] I. F. Abdin, Y. P. Fang, and E. Zio, "A modeling and optimization framework for power systems design with operational flexibility and resilience against extreme heat waves and drought events," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 706–719, Sep. 2019.

[56] 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.

[57] C. Wang, Y. Hou, F. Qiu, S. Lei, and K. Liu, "Resilience enhancement with sequentially proactive operation strategies," *IEEE Trans Power Syst.*, vol. 32, no. 4, pp. 2847–2857, Jul. 2017.

[58] D. T. Ton and W.-T. P. Wang, "A more resilient grid: The U.S. Department of energy joins with stakeholders in an R&D plan," *IEEE Power Energy Mag.*, vol. 13, no. 3, pp. 26–34, May/Jun. 2015.

[59] R. J. Campbell, *Weather-Related Power Outages and Electric System Resiliency*. Washington, DC, USA: Congressional Research Service, Aug. 2012.

[60] M. McGranaghan, M. Olearczyk, and C. Gellings, "Enhancing distribution resiliency: Opportunities for applying innovative technologies," Palo Alto, CA, USA: EPRI, 2013.

[61] 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.

[62] 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.

[63] Z. Li and M. Shahidehpour, "Role of microgrids in enhancing power system resilience," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2017, pp. 1–5.

[64] X. Liu, K. Hou, H. Jia, Y. Mu, X. Yu, Y. Wang, and J. Dong, "A quantified resilience assessment approach for electrical power systems considering multiple transmission line outages," in *Proc. IEEE Elect. Power Energy Conf. (EPEC)*, Oct. 2017, pp. 1–5.

[65] J. Mitra and S. J. Ranade, "Power system hardening through autonomous, customer-driven microgrids," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2007, pp. 1–4.

[66] 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.

[67] J. Qiu, L. J. Reedman, Z. Y. Dong, K. Meng, H. Tian, and J. Zhao, "Network reinforcement for grid resiliency under extreme events," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2017, pp. 1–5.

[68] M. H. Amirioun, F. Aminifar, and H. Lesani, "Towards proactive scheduling of microgrids against extreme floods," *IEEE Trans. Smart Grid*, vol. 9, no. 4, pp. 3900–3902, Jul. 2018.

[69] 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.

[70] P. Dehghanian and S. Aslan, "Enhancing electric safety by improving system resiliency in face of extreme emergencies," in *Proc. IEEE IAS Elect. Saf. Workshop (ESW)*, Jan. 2017, p. 1.

[71] 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. 2017.

[72] M. Zare, A. Abbaspour, M. Fotuhi-Firuzabad, and M. Moeini-Aghtaie, "Increasing the resilience of distribution systems against hurricane by optimal switch placement," in *Proc. Conf. Elect. Power Distrib. Netw. Conf. (EPDC)*, Apr. 2017, pp. 7–11.

[73] R. Eskandarpour, A. Khodaei, and A. Arab, "Improving power grid resilience through predictive outage estimation," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2017, pp. 1–5.

[74] M. Panteli, P. A. Crossley, D. S. Kirschen, and D. J. Sobajic, "Assessing the impact of insufficient situation awareness on power system operation," *IEEE Trans. Power Syst.*, vol. 28, no. 3, pp. 2967–2977, Aug. 2013.

[75] M. Panteli, D. S. Kirschen, P. A. Crossley, and D. J. Sobajic, "Enhancing situation awareness in power system control centers," in *Proc. IEEE Int. Multi-Disciplinary Conf. Cognit. Methods Situation Awareness Decis. Support (CogSIMA)*, Feb. 2013, pp. 254–261.

[76] R. Eskandarpour and A. Khodaei, "Machine learning based power grid outage prediction in response to extreme events," *IEEE Trans. Power Syst.*, vol. 32, no. 4, pp. 3315–3316, Jul. 2017.

[77] P. Van Hentenryck, C. Coffrin, and R. Bent, "Vehicle routing for the last mile of power system restoration," in *Proc. 17th Power Syst. Comput. Conf. (PSCC)*, Stockholm, Sweden, Aug. 2011, pp. 1–9.

[78] T. Jin, N. Mai, Y. Ding, L. Vo, and R. Dawud, "Planning for distribution resilience under variable generation: Prevention, surviving and recovery," in *Proc. IEEE Green Technol. Conf. (GreenTech)*, Apr. 2018, pp. 49–56.

[79] J. Johansson and H. Hassel, "An approach for modelling interdependent infrastructures in the context of vulnerability analysis," *Rel. Eng. Syst. Saf.*, vol. 95, no. 12, pp. 1335–1344, 2010.

[80] A. Arif, S. Ma, and Z. Wang, "Optimization of transmission system repair and restoration with crew routing," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2016, pp. 1–6.

[81] B. Simon, C. Coffrin, and P. Van Hentenryck, "Randomized adaptive vehicle decomposition for large-scale power restoration," in *Proc. Int. Conf. Integr. Artif. Intell. (AI) Oper. Res. (OR) Techn. Constraint Program.* Berlin, Germany: Springer, May 2012, pp. 379–394.

[82] C. E. A. Mulligan and M. Olsson, "Architectural implications of smart city business models: An evolutionary perspective," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 80–85, Jun. 2013.

[83] 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.

[84] B. E. Hamilton, J. A. Martin, T. J. Mathews, P. D. Sutton, and S. J. Ventura, *The Effect of Hurricane Katrina: Births in the U.S. Gulf Coast Region, Before and After the Storm*. New York, NY, USA: National Vital Statistics Reports, 2009.

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

[86] M. Rollins, "The hardening of utilitiy lines-implications for utility pole design and use," North Amer. Wood Pole Council, North America, Tech. Rep., 2007.

[87] A. Kenward and U. Raja, "Blackout: Extreme weather, climate change and power outages," *Climate Central*, vol. 10, pp. 1–23, Apr. 2014.

[88] A. Gholami, T. Shekari, M. H. Amirioun, F. Aminifar, M. H. Amini, and A. Sargolzaei, "Toward a consensus on the definition and taxonomy of power system resilience," *IEEE Access*, vol. 6, pp. 32035–32053, 2018.

[89] P. Hoffman, W. Bryan, M. Farber-DeAnda, M. Cleaver, C. Lewandowski, and K. Young, "Hardening and resiliency, US energy industry response to recent hurricane seasons," Office Electr. Del. Energy Rel., U.S. Dept. Energy, Washington, DC, USA, OE/ISER Final Rep., 2010.

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

[91] G. Li, P. Zhang, P. B. Luh, W. Li, Z. Bie, C. Serna, and Z. Zhao, "Risk analysis for distribution systems in the northeast U.S. Under wind storms," *IEEE Trans. Power Syst.*, vol. 29, no. 2, pp. 889–898, Mar. 2013.

[92] N. Abi-Samra and W. Henry, "Actions before... and after a flood," *IEEE Power Energy Mag.*, vol. 9, no. 2, pp. 52–58, Mar./Apr. 2011.

[93] R. Brown, "Undergrounding assessment phase 1 final report: Literature review and analysis of electric distribution overhead to underground conversion," Quanta Technol., Florida, FL, USA, Tech. Rep., 2007.

[94] *Study of the Feasibility and Reliability of Undergrounding Electric Distribution Lines in District of Columbia*, Shaw Consultants Int., Houston, TX, USA, 2010.

[95] *Florida Power and Light Company Annual Reliability Filing to the Florida Public Service Commission*, Florida Power Light Company, Juno Beach, FL, USA, 2017.

[96] R. Abrams and B. Lawsky, "Moreland commission on utility storm preparation and response," New York, NY, USA, Tech. Rep., 2013.

[97] L. Xu and R. E. Brown, "Undergrounding assessment phase 3 report: Ex ante cost and benefit modeling," Quanta Technol., Raleigh, NC, USA, Tech. Rep., 2008.

[98] *Underground Electric Transmission Lines*, Public Service Commission Wisconsin, Madison, WI, USA, 2011.

[99] K. Kopsidas and S. Liu, "Power network reliability framework for integrating cable design and ageing," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1521–1532, Aug. 2017.

[100] Ø. Hov, U. Cubasch, E. Fischer, P. Höppe, T. Iversen, N. G. Kvamstø, and B. Schädler, "Extreme weather events in Europe: Preparing for climate change adaptation," Norwegian Meteorol. Inst., Oslo, Norway, Tech. Rep. 20, 2013.

[101] 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, Jan. 2014.

[102] R. E. Brown, "Cost-benefit analysis of the deployment of utility infrastructure upgrades and storm hardening programs," Quanta Technol., Raleigh, NC, USA, Tech. Rep. 36375, Jun. 2009.

[103] J. M. Boggess, G. W. Becker, and M. K. Mitchell, "Storm & flood hardening of electrical substations," in *Proc. IEEE PES T&D Conf. Expo.*, Apr. 2014, pp. 1–5.

[104] Z. Fang, G. Dolan, A. Sebastian, and P. B. Bedient, "Case study of flood mitigation and hazard management at the texas medical center in the wake of tropical storm Allison in 2001," *Natural Hazards Rev.*, vol. 15, no. 3, p. 05014001, 2014.

[105] A. M. Salman, Y. Li, and M. G. Stewart, "Evaluating system reliability and targeted hardening strategies of power distribution systems subjected to hurricanes," *Rel. Eng. Syst. Saf.*, vol. 144, no. 3, pp. 319–333, Dec. 2015.

[106] S. Bjarnadottir, Y. Li, and M. G. Stewart, "Hurricane risk assessment of power distribution poles considering impacts of a changing climate," *J. Infrastruct. Syst.*, vol. 19, no. 1, pp. 12–24, 2012.

[107] S. Ma, B. Chen, and Z. Wang, "Resilience enhancement strategy for distribution systems under extreme weather events," *IEEE Trans. Smart Grid*, vol. 9, no. 2, pp. 1442–1451, Mar. 2018.

[108] A. Shafieezadeh, U. P. Onyewuchi, M. M. Begovic, and R. DesRoches, "Age-dependent fragility models of utility wood poles in power distribution networks against extreme wind hazards," *IEEE Trans. Power Del.*, vol. 1, no. 29, pp. 131–139, Feb. 2014.

[109] D. Sherpa, "Affordable solution for earthquake resistant building construction in haiti," South Alberta Inst Technol., Calgary, AB, Canada, Tech. Rep., 2010, pp. 1–11.

[110] A. Navarro-Espinosa, R. Moreno, T. Lagos, F. Ordoñez, R. Sacaan, S. Espinoza, and H. Rudnick, "Improving distribution network resilience against earthquakes," in *Proc. IET Int. Conf. Resilience Transmiss. Distrib. Netw. (RTDN)*, Sep. 2017, pp. 1–6.

[111] S. A. Zareei, M. Hosseini, and M. Ghafory-Ashtiany, "Seismic failure probability of a 400 kV power transformer using analytical fragility curves," *Eng. Failure Anal.*, vol. 70, pp. 273–289, Dec. 2016.

[112] S. C. Goel, W. C. Liao, B. M. Reza, and S. H. Chao, "Performance-based plastic design (PBPD) method for earthquake-resistant structures: An overview," *Struct. Des. Tall Special Building*, vol. 19, nos. 1–2, pp. 115–137, 2010.

[113] P. De Martini, "More than smart: A framework to make the distribution grid more open, efficient and resilient," Resnick Sustainability Inst., California, CA, USA, Tech. Rep., 2014.

[114] G. Allicance, "Improving electric grid reliability and resilience: Lessons learned from superstorm sandy and other extremes events," GridWise Alliance, Tech. Rep., 2013, pp. 1–36.

[115] D. N. Bresch and E. W. Group, "Building a resilient energy gulf coast: Executive report," ETH Zürich, Zürich, Switzerland, Tech. Rep., 2010.

[116] M. Davis, "Power failure: How climate change puts our electricity at risk–and what we can do," Union Concerned Scientists, Tech. Rep., 2014.

[117] P. A. Kuntz, R. D. Christie, and S. S. Venkata, "Optimal vegetation maintenance scheduling of overhead electric power distribution systems," *IEEE Trans. Power Del.*, vol. 17, no. 4, pp. 1164–1169, Oct. 2002.

[118] S. Ma, L. Su, Z. Wang, F. Qiu, and G. Guo, "Resilience enhancement of distribution grids against extreme weather events," *IEEE Trans. Power Syst.*, vol. 33, no. 5, pp. 4842–4853, Sep. 2018.

[119] P. Zahodiakin, "Making distribution grids stronger, more resilient," *EPRI J.*, vol. 4, pp. 4–8, Aug. 2016.

[120] R. Barben, "Vulnerability assessment of electric power supply under extreme weather conditions," M.S. thesis, EPFL, Lausanne, Switzerland, 2010.

[121] *The Resilience of the Electricity System Oral and Written Evidence*, Sci. Technol. Select Committee, London, U.K., 2014, pp. 1–651.

[122] R. E. Brown, "Hurricane hardening efforts in Florida," in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Electr. Energy 21st Century*, Jul. 2008, pp. 1–7.

[123] C. Ji, Y. Wei, H. Mei, J. Calzada, M. Carey, S. Church, T. Hayes, B. Nugent, G. Stella, M. Wallace, J. White, and R. Wilcox, "Large-scale data analysis of power grid resilience across multiple US service regions," *Nature Energy*, vol. 1, no. 5, p. 16052, 2016.

[124] C. Ji, Y. Wei, and H. V. Poor, "Resilience of energy infrastructure and services: Modeling, data analytics, and metrics," *Proc. IEEE*, vol. 105, no. 7, pp. 1354–1366, Jul. 2017.

[125] C. Ren and Y. Xu, "A fully data-driven method based on generative adversarial networks for power system dynamic security assessment with missing data," *IEEE Trans. Power Syst.*, vol. 34, no. 6, pp. 5044–5052, Nov. 2019.

[126] Y. Chen, Y. Wang, D. S. Kirschen, and B. Zhang, "Model-free renewable scenario generation using generative adversarial networks," *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 3265–3275, May 2018.

[127] Q. Huang, W. Hao, J. Tan, R. Fan, and Z. Huang, "Adaptive power system emergency control using deep reinforcement learning," 2019, *arXiv:1903.03712*. [Online]. Available: https://arxiv.org/abs/1903.03712

[128] J. Yan, H. He, X. Zhong, and Y. Tang, "Q-learning-based vulnerability analysis of smart grid against sequential topology attacks," *IEEE Trans. Inf. Forensics Security*, vol. 12, no. 1, pp. 200–210, Jan. 2017.

[129] R. Eskandarpour and A. Khodaei, "Probabilistic load curtailment estimation using posterior probability model and twin support vector machine," *J. Mod. Power Syst. Clean Energy*, vol. 7, no. 4, pp. 665–675, 2019.

[130] Z. Liang, A. Kavousifard, and W. Su, "Resilient restoration for distribution system operators when facing extreme events," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2018, pp. 1–6.

[131] M. Su and J. Wang, "Energy management systems in microgrid operations," *Energy Convers. Manage.*, vol. 25, no. 8, pp. 45–60, Oct. 2012.

[132] 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.

[133] *Severe Impact Resilience: Considerations and Recommendations*, Severe Impact Resilience Task Force, North Amer. Elect. Rel. Corp., Atlanta, GA, USA, 2012.

[134] A. Gholami, F. Aminifar, and M. Shahidehpour, "Front lines against the darkness: Enhancing the resilience of the electricity grid through microgrid facilities," *IEEE Electrific. Mag.*, vol. 4, no. 1, pp. 18–24, Mar. 2016.

[135] N. Hatziargyriou, Eds., *Microgrids: Architectures and Control*. Hoboken, NJ, USA: Wiley, 2014.

[136] R. H. Lasseter and P. Piagi, "Microgrid: A conceptual solution," in *Proc. IEEE 35th Annual Power Electron. Spec. Conf.*, vol. 6, Jun. 2004, pp. 4285–4291.

[137] K. Boroojeni, M. H. Amini, A. Nejadpak, T. Dragicevic, S. S. Iyengar, and F. Blaabjerg, "A novel cloud-based platform for implementation of oblivious power routing for clusters of microgrids," *IEEE Access*, vol. 5, pp. 607–619, 2017.

[138] L. Che, M. Khodayar, and M. Shahidehpour, "Only connect: Microgrids for distribution system restoration," *IEEE Power Energy Mag.*, vol. 1, no. 12, pp. 70–81, Jan./Feb. 2014.

[139] 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.

[140] 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.

[141] C. Gouveia, J. Moreira, C. L. Moreira, and J. A. P. Lopes, "Coordinating storage and demand response for microgrid emergency operation," *IEEE Trans. Smart Grid*, vol. 4, no. 4, pp. 1898–1908, Dec. 2013.

[142] A. Gholami, T. Shekari, and S. Grijalva, "Proactive management of microgrids for resiliency enhancement: An adaptive robust approach," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 470–480, Jan. 2017.

[143] M. H. Amirioun, F. Aminifar, and H. Lesani, "Resilience-oriented proactive management of microgrids against windstorms," *IEEE Trans. Power Syst.*, vol. 33, no. 4, pp. 4275–4284, Jul. 2018.

[144] S. Espinoza, M. Panteli, P. Mancarella, and H. Rudnick, "Multi-phase assessment and adaptation of power systems resilience to natural hazards," *Electr. Power Syst. Res.*, vol. 136, pp. 352–361, Jun. 2016.

[145] C. Shao, M. Shahidehpour, X. Wang, X. Wang, and B. Wang, "Integrated planning of electricity and natural gas transportation systems for enhancing the power grid resilience," *IEEE Trans. Power Syst.*, vol. 32, no. 6, pp. 4418–4429, Nov. 2017.

[146] 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.

[147] 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.

[148] 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.

[149] 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.

[150] T. Ding, Y. Lin, G. Li, and Z. Bie, "A new model for resilient distribution systems by microgrids formation," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 4145–4147, Sep. 2017.

[151] 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.

[152] B. Chen, C. Chen, J. Wang, and K. L. Butler-Purry, "Sequential service restoration for unbalanced distribution systems and microgrids," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1507–1520, Mar. 2018.

[153] M. A. Mohamed, A. M. Eltamaly, A. I. Alolah, and A. Y. Hatata, "A novel framework-based cuckoo search algorithm for sizing and optimization of grid-independent hybrid renewable energy systems," *Int. J. Green Energy*, vol. 16, no. 1, pp. 86–100, Oct. 2018.

[154] H. Gao, Y. Chen, S. Mei, S. Huang, and Y. Xu, "Resilience-oriented pre-hurricane resource allocation in distribution systems considering electric buses," *Proc. IEEE*, vol. 105, no. 7, pp. 1214–1233, Jul. 2017.

[155] H. Liu, R. A. Davidson, D. V. Rosowsky, and J. R. Stedinger, "Negative binomial regression of electric power outages in hurricanes," *J. Infrastruct. Syst.*, vol. 11, no. 4, pp. 258–267, 2005.

[156] S. D. Guikema, R. Nateghi, S. M. Quiring, A. Staid, A. C. Reilly, and M. Gao, "Predicting hurricane power outages to support storm response planning," *IEEE Access*, vol. 2, pp. 1364–1373, 2014.

[157] R. Nateghi, S. D. Guikema, and S. M. Quiring, "Forecasting hurricane-induced power outage durations," *Natural Hazards*, vol. 74, no. 3, pp. 1795–1811, 2014.

[158] M. Bynum, A. Castillo, J. P. Watson, and C. D. Laird, "Evaluating demand response opportunities for power systems resilience using MILP and MINLP Formulations," *AIChE J.*, vol. 65, no. 7, p. e16508, 2019.

[159] W. Sun, C. C. Liu, and S. Liu, "Black start capability assessment in power system restoration," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2011, pp. 1–7.

[160] F. Qiu, J. Wang, C. Chen, and J. Tong, "Optimal black start resource allocation," *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 2493–2494, May 2015.

[161] J. Shang, X. Sheng, J. H. Zhang, and W. Zhao, "The optimized allocation of mobile emergency generator based on the loads importance," in *Proc. Asia–Pacific Power Energy Eng. Conf.*, Mar. 2009, pp. 1–4.

[162] C. Wang, Y. Hou, Z. Qin, C. Peng, and H. Zhou, "Dynamic coordinated condition-based maintenance for multiple components with external conditions," *IEEE Trans. Power Del.*, vol. 30, no. 5, pp. 2362–2370, Oct. 2015.

[163] S. Zhang and V. Vittal, "Wide-area control resiliency using redundant communication paths," *IEEE Trans. Power Syst.*, vol. 29, no. 5, pp. 2189–2199, Sep. 2014.

[164] V. Vittal, "Design of wide-area power system damping controllers resilient to communication failures," in *Proc. IEEE Power Energy Soc. General Meeting (PESGM)*, Jul. 2016, p. 1.

[165] 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.

[166] 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.

[167] 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.

[168] F. Ren, M. Zhang, D. Soetanto, and X. Su, "Conceptual design of a multi-agent system for interconnected power systems restoration," *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 732–740, May 2012.

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

[170] R. Eskandarpour, H. Lotfi, and A. Khodaei, "Optimal microgrid placement for enhancing power system resilience in response to weather events," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2016, pp. 1–6.

[171] M. Shahidehpour, "Role of smart microgrid in a perfect power system," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, p. 1.

[172] V. Meyer, C. Myres, and N. Bakshi, "The vulnerabilities of the power-grid system: Renewable microgrids as an alternative source of energy," *J. Bus. Continuity Emergency Planning*, vol. 4, no. 2, pp. 142–153, 2010.

[173] P. Agrawal, "Overview of DOE microgrid activities," in *Proc. Symp. Microgrid*, Montreal, QC, USA, Jun. 2006, pp. 1–32.

[174] A. G. Tsikalakis and N. D. Hatziargyriou, "Operation of microgrids with demand side bidding and continuity of supply for critical loads," *Eur. Trans. Elect. Power*, vol. 21, no. 2, pp. 1238–1254, 2011.

[175] S. Rahman, "Framework for a resilient and environment-friendly microgrid with demand-side participation," in *Proc. IEEE Power Energy Soc. Gen. Meeting-Convers. Del. Electr. Energy 21st Century*, Jul. 2008, p. 1.

[176] P. Li, P. Degobert, B. Robyns, and B. Francois, "Implementation of interactivity across a resilient microgrid for power supply and exchange with an active distribution network," in *Proc. CIRED Seminar SmartGrids Distrib.*, 2008, pp. 1–4.

[177] F. O. Resende, N. J. Gil, and J. P. Lopes, "Service restoration on distribution systems using multi-microgrids," *Eur. Trans. Electr. Power*, vol. 21, no. 2, pp. 1327–1342, 2011.

[178] C. M. Colson, M. H. Nehrir, and R. W. Gunderson, "Distributed multi-agent microgrids: A decentralized approach to resilient power system self-healing," in *Proc. 4th Int. Symp. Resilient Control Syst.*, Aug. 2011, pp. 83–88.

[179] J. Hurtt and L. Mili, "Residential microgrid model for disaster recovery operations," in *Proc. IEEE Grenoble Conf.*, Jun. 2013, pp. 1–6.

[180] S. Cano-Andrade, M. R. Von Spakovsky, A. Fuentes, C. L. Prete, B. F. Hobbs, and L. Mili, "Multi-objective optimization for the sustainable-resilient synthesis/design/operation of a power network coupled to distributed power producers via microgrids," in *Proc. ASME Int. Mech. Eng. Congr. Expo. Amer. Soc.*, Nov. 2012, pp. 1393–1408.

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

[182] A. Hussain, B. Van-Hai, and H.-M. Kim, "Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience," *Appl. Energy*, vol. 240, pp. 56–72, Apr. 2019.

[183] T. Basso, *IEEE 1547 and 2030 Standards for Distributed Energy Resources Interconnection and Interoperability With the Electricity Grid*, Standard NREL/TP-5D00-63157, National Renewable Energy Laboratory, Golden, CO, USA, 2014.

[184] S. Liu, Y. Hou, C. C. Liu, and R. Podmore, "The healing touch: Tools and challenges for smart grid restoration," *IEEE Power Energy Mag.*, vol. 12, no. 1, pp. 54–63, Jan./Feb. 2013.

[185] A. M. Eltamaly, M. A. Mohamed, M. S. Al-Saud, and A. I. Alolah, "Load management as a smart grid concept for sizing and designing of hybrid renewable energy systems," *Eng. Optim.*, vol. 49, no. 10, pp. 1813–1828, 2017.

[186] M. A. Mohamed and A. M. Eltamaly, *Modeling and Simulation of Smart Grid Integrated with Hybrid Renewable Energy Systems*. New York, NY, USA: Springer, 2018.

MOHAMED A. MOHAMED (M'16) received the B.Sc. and M.Sc. degrees from Minia University, Minia, Egypt, in 2006 and 2010, respectively, and the Ph.D. degree from King Saud University, Riyadh, Saudi Arabia, in 2016. He joined the College of Electrical Engineering and Automation, Fuzhou University, China, as a Postdoctoral Research Fellow, in 2018. He has been a Faculty Member of the Department of Electrical Engineering, College of Engineering, Minia University, since 2008. His current research interests include renewable energy, energy management, power electronics, power quality, optimization, smart islands, and smart grids. He has supervised multiple M.Sc. and Ph.D. theses, worked on a number of technical projects, and published various articles and books. He has also joined the editorial board of some scientific journals and the steering committees of many international conferences.

TAO CHEN received the B.S. degree in electrical engineering from Anhui University, in 2012, the M.S. degree in electrical engineering from the Tampere University of Technology, in 2014, and the Ph.D. degree from the University of Michigan–Dearborn, in 2018. He is currently a Postdoctoral Associate with Virginia Tech. His research interests include smart grids, electric vehicles, and machine learning applications.

WENCONG SU (S'06–M'13–SM'18) received the B.S. degree (Hons.) from Clarkson University, Potsdam, NY, USA, in 2008, the M.S. degree from Virginia Tech, Blacksburg, VA, USA, in 2009, and the Ph.D. degree from North Carolina State University, Raleigh, NC, USA, in 2013, all in electrical and computer engineering. He is currently an Associate Professor with the Department of Electrical and Computer Engineering, University of Michigan–Dearborn. He is a registered Professional Engineer (P.E.) in the State of Michigan. His current research interests include power and energy systems, energy Internet, electrified transportation systems, and cyber-physical systems. He is an Editor of the IEEE TRANSACTIONS ON SMART GRID and an Associate Editor of IEEE ACCESS.

TAO JIN (SM'19) was born in Hubei, China, in 1976. He received the B.S. and M.S. degrees from Yanshan University, in 1998 and 2001, respectively, and the Ph.D. degree in electrical engineering from Shanghai Jiao Tong University, in 2005.

From 2005 to 2007, he was a Postdoctoral Researcher with Shanghai Jiao Tong University. During this time, he was in charge of a research group in the biggest dry-type transformer company in Asia, Sunten Electrical Company, Ltd., to develop a new transformer technology for distribution grids. From 2008 to 2009, he was a Research Scientist with Virginia Tech, Blacksburg, USA, where he was involved in design and testing of PMU technology and GPS/internet-based power system frequency monitoring networks. In 2010, he joined Imperial College London, U.K., as a European Union Marie Curie Research Fellow, where he was focused on electrical technologies related to smart grids. He is currently a Professor with the College of Electrical Engineering and Automation, Fuzhou University, China. He has published about 110 articles. He is a member of the IEEE Power and Energy Society and the IEEE Industrial Electronics Society. He is also a special Committee Member of the Chinese Society of Electrical Engineering and the China Electro Technical Society. He currently serves as an Associate Editor for the *China Measurement and Testing Technology* and other journals.

• • •