IET Energy Systems Integration

Review Article

Resilient distribution system leveraging distributed generation and microgrids: a review

eISSN 2516-8401
Received on 30th November 2019
Revised 5th August 2020
Accepted on 31st August 2020
E-First on 12th November 2020
doi: 10.1049/iet-esi.2019.0134
www.ietdl.org

Guodong Liu[1], Tao Jiang[2] ✉, Thomas B. Ollis[1], Xue Li[2], Fangxing Li[3], Kevin Tomsovic[3]
[1]*Oak Ridge National Laboratory, One Bethel Valley Road, P.O. Box 2008, MS 6007, Oak Ridge, TN 37831, USA*
[2]*Department of Electrical Engineering, Northeast Electric Power University, No.169 Changchun Road, Jilin 132012, People's Republic of China*
[3]*Department of Electrical Engineering and Computer Science, The University of Tennessee, Knoxville, 1520 Middle Dr., Knoxville, TN 37996, USA*
✉ *E-mail: tjiang@neepu.edu.cn*

Abstract: With the aging of electricity transmission and distribution infrastructures and increasing intensity of extreme weather events, the aggravated vulnerability of electric distribution systems to extreme weather events has motivated the study of resilient distribution systems. This study presents a review of the state-of-the-art research on distribution grid resilience. First, the definition and quantifying metrics of resilience in the electrical distribution system are summarised. Second, the long-term and short-term measures to enhance the distribution system resilience are discussed. In particular, the recent studies on distributed generation and microgrid-assisted resilience enhancements are reviewed. Finally, recommendations for future research are presented.

1 Introduction

The planning and operation of the electrical distribution system has traditionally focused on improving the reliability, affordability, and efficiency of customers' electricity supply [1]. The goal of electrical distribution system planning and operation is to design and operate the distribution grid in a way that satisfies the electricity demands of customers in the most reliable, economical, and efficient way. The outages considered in the context of reliability are mostly 'N−1' or 'N−2' scenarios. Reliability metrics, such as the system average interruption duration index (SAIDI), the system average interruption frequency index (SAIFI), the customer average interruption duration index, and the customer average interruption frequency index (CAIFI) are used to evaluate electricity supply quality of over a long period of time [2]. However, these reliability metrics cannot evaluate the performance of distribution systems under extreme events (e.g. hurricanes, earthquakes, tsunamis, etc.), which usually damage many components and result in outages for a long time. For example, Superstorm Sandy in 2012 was an 'N-90' event with estimated damage totaling nearly $50 billion, which resulted in power outages of up to 30 days for a certain area on the east coast of the United States [3]. The Southern China snowstorm in 2008 caused the failure of 129 lines and >2000 substations, which caused 14.66 million households to be without electricity supply [4]. Under these circumstances, the capability of a power system to maintain and restore supply to customers during and after extreme events is often mentioned as resilience, which cannot be captured by reliability metrics [5].

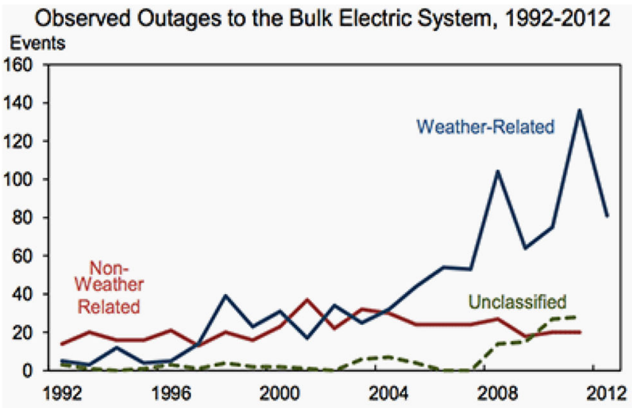

Fig. 1 *Observed outages to the bulk of the US electric system between 1992 and 2012*

In recent years, the frequency and intensity of weather-related incidents and natural disasters have been increasing due to excessive greenhouse gas emissions. As a result, the number of observed outages of the electric power system caused by weather-related incidents has grown significantly over the past decade, as shown in Fig. 1 [6]. Extreme weather is the leading cause of electric power outages in the United States, accounting for 80% of all outages between 2003 and 2012. Extreme weather-related outages cost the United States $20–55 billion annually, according to recent estimates [7]. Additionally, the functions of other critical infrastructures – such as water, health care, and emergency response – rely heavily on electricity supply from utilities. Therefore, determining how to effectively enhance the resilience of the electric power system has become an urgent need and attracted worldwide intention from academia and industry. Developing effective strategies beyond the traditional reliability view to improve grid resilience is fundamentally important.

Although there are many existing publications related to defining and enhancing resilience strategies, resilience is an emerging concept in power systems, which still lack a standard definition. One for the most often used definitions of resiliency is in the 2013 US Presidential Policy Directive 21 (PPD-21), which defines resilience as, 'the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents' [6]. In the context of electric power systems, PJM defines resilience as, 'preparing for, operating through and recovering from a high-impact, low-frequency event' [8]. According to the IEEE Power and Energy Society Task Force on Definition and Quantification of Resilience, resilience is defined as, 'the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event' [9]. Nevertheless, these definitions share a common comprehension, which focuses on the ability of an infrastructure or

Table 1 Comparison of resilience and reliability

Resilience	Reliability
consider low-probability high-impact extreme events	consider high-probability low-impact non-extreme events
static	dynamic multistage process
assessed over a certain duration of time (e.g. 1 year)	assessed before or after an event
quantifies the states of the distribution system before, during, and after the extreme events, as well as the transition process among states	quantifies the state of the distribution system after an event
captures effects on customer interruption time	captures effects on customer interruption time and infrastructure recovery time
not well defined, and quantifying metrics still must be defined	well defined, and quantifying metrics include SAIFI, SAIDI, CAIFI, CAIDI, and so on

system to prepare for and adapt to low-probability high-impact incidents and withstand and recover rapidly from disruptions.

As electricity transmission and distribution infrastructures age and the intensity of extreme weather events increases, the electric distribution system's vulnerability to extreme weather events increases. However, the customers' expectation for efficient and reliable electricity supply has also been increasing due to modern technologies' reliance on electricity. Most electrical utilities have recognised the necessity of enhancing grid resilience to low-probability high-impact incidents. Generally, these enhancements can be divided into two categories: long-term and short-term. The long-term enhancements refer to the system's long-term structural planning and design to improve resilience to extreme weather events. Although there has been extensive research on power distribution system planning, they mostly focus on improving the power distribution system reliability with minimised investment and operating costs [1]. The fault scenarios considered in such research are usually credible events modelled by the '*N*–1' rule, which does not apply to distribution system performance under extreme events. The long-term enhancements to the resilience of electrical distribution systems include hardening the distribution grid (e.g. reinforcing towers and poles, elevating substations, moving feeders underground, building redundant transmission routes, better vegetation management), improving the incident management process (e.g. improving extreme weather forecast and damage estimate, rerouting power flow to feeders in areas less affected by extreme weather, establishing extended mutual aid agreements, reinforcing emergency preparedness), and investing in smart grid technologies (e.g. installing battery storage devices and distributed generation [DG], deploying dedicated fibre-optic reliable and interoperable communication networks, optimal placement of sectionalising switches). On the other hand, short-term enhancements to electrical distribution system resilience mainly focus on improving the operational ability to isolate the damaged components, mitigate the impacts, maintain the electricity supply for critical customers, and restore the supply to other affected customers as soon as possible. Short-term enhancements include improving system situational awareness, recognising available flexible resources, developing restoration strategies, and so on. Although long-term system hardening and resilience investments are very important, short-term system situational awareness and restoration in response to extreme weather events is also indispensable for achieving resilient electric distribution systems.

One of the latest research directions is to improve the power system resiliency by deploying microgrids. A *microgrid* is a group of interconnected DGs, energy storage systems (ESSs), and collocated loads with the ability to intentionally disconnect from the main grid and continue to supply the islanded portion without any interruption [10]. Microgrids enhance the resiliency of the power system by lowering the probability and amount of load shedding, preventing cascading blackouts, and reducing the time of restoration [11]. Due to the operational flexibility and self-healing capabilities of microgrids, more and more microgrids have been deployed in utilities, universities and hospital campuses, military bases, and industrial parks in recent years [12]. Furthermore, *networked microgrids*, which are defined as the aggregation of interconnected adjacent microgrids, offer a more efficient and resilient alternative to individual microgrids. Researching restoration strategies that leverage microgrids have gained substantial attention in recent decades. However, achieving a practical resilient restoration strategy by integrating existing components and these emerging technologies is still challenging.

The main goal of this paper is to provide a comprehensive overview of the resilience in the context of electrical distribution systems. First, the definition and quantifying metrics of resilience are summarised. Based on this, the long-term and short-term enhancements to the resilience of the electrical distribution system are reviewed and categorised. In particular, the roles that DGs and microgrids play in enhancing electrical distribution system resilience are analysed. Then, the research gaps are identified, and future research works are recommended. The main contributions of this paper are as follows:

(i) Summarises the definition and quantifying metrics of resilience in the context of electrical distribution systems.
(ii) Reviews long-term and short-term enhancements to the resilience of electrical distribution systems.
(iii) Reviews existing research on the roles that microgrids could play in the enhancement of electrical distribution system resilience.
(iv) Identifies the limitations and gaps of current research and practices and presents recommendations for future research.

The remaining of this paper is organised as follows. Section 2 introduces the definition and quantifying metrics of resilience. The long-term and short-term enhancements to electrical distribution system resilience are reviewed in Section 3. Existing research on the roles that microgrids could play to enhance electrical distribution system resilience is summarised in Section 4. Research gaps and recommendation for future research are presented in Section 5. Finally, Section 6 concludes the paper.

2 Understanding resilience

2.1 Concept of resilience

An easy way to understand the essence of resilience is by outlining the differences between resilience and reliability. The reliability of an electrical distribution system is the ability to deliver an uninterrupted electricity supply to customers. As mentioned in Section 1, resilience indicates the performance of a distribution system against low-probability high-impact events, whereas reliability indicates the performance of a distribution system against high-probability low-impact events. Specifically, electrical distribution system reliability is often evaluated by a historical assessment, which usually excludes events such as weather, declared emergencies, or disasters that affect over 10% of the utility's customers. These excluded events are exactly the sort of trigger events one should watch out for when accessing the resilience of an electrical distribution system. Additionally, resilience quantifies the states of the distribution system before, during, and after the extreme events, as well as the transition process among these states. Thus, resilience evaluation is a dynamic process that involves preparation before the extreme events, the operation during the extreme event, and the response after the extreme event. The key characteristics differentiating the concept of resilience from that of reliability are summarised in Table 1.

The resilience trapezoid has been widely used to illustrate the key features of resilience, as shown in Fig. 2 [13]. The multistage resilience trapezoid demonstrates the essential features of an electrical distribution system that are required to survive any extreme events. As shown in Fig. 2*a*, the electrical distribution system will undergo three static states – pre-event state, degraded state, and post-event state – and two transition states – degradation

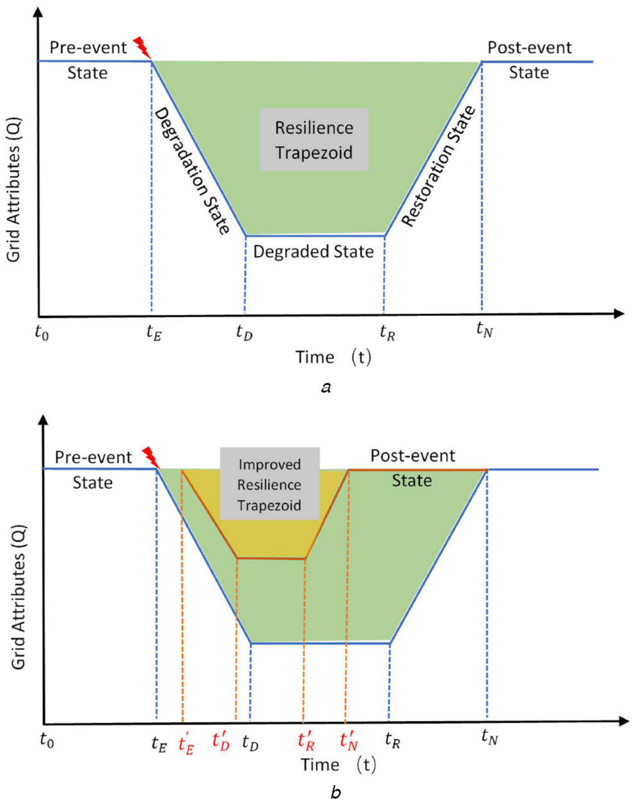

Fig. 2 *Resilience trapezoid associated with an extreme event*
(a) Original resilience trapezoid, ***(b)*** Improved resilience trapezoid

state and restoration state – with the evolving grid attributes as the event occurs and develops. The grid attributes include but are not limited to the system functionality, system performance, system flexibility, and the health degree of system/organisational infrastructure. In the *pre-event state*, the electrical distribution system is considered to be under the normal conditions with perfect grid attributes. In this state, the system should be prepared for the upcoming events. For example, mitigation strategies should be developed to prevent or minimise the damages caused by the coming extreme events. The attack/event happens at the time t_E, and the grid attributes start to degrade. In the *degradation state*, mitigation or corrective actions can help alleviate the damaging effects caused by the extreme events. The degradation state ends at the time t_D when the grid attributes reach their worst conditions. Then, the system stays in the degraded state before the restoration process starts. In the degraded state, the system condition is evaluated based on the damages observed or estimated. A corresponding restoration plan is then designed. Following the degraded state, the restoration process starts at the time t_R. The grid attributes start to recover as the restoration actions are deployed. In the *restoration state*, the repair crew, spare parts, transportation, and temporary power supply should be carefully coordinated to reduce the restoration time and restore the grid attributes as much as possible. The restoration state ends at the time t_N when the grid attributes reach the level in the pre-event state and the system goes into the post-event state. The *post-event state* is important since a post-analysis of the whole event will be conducted to identify the weakness of the electrical distribution system and implement long-term enhancement strategies. The ability of the electrical distribution system to cope with similar events in the future will be improved.

The resilience trapezoid accurately reflects the four main features of resilience summarised by the US NIAC: robustness, resourcefulness, rapid recovery, and adaptability [14]. Robustness indicates that the electrical distribution system should be prepared for the extreme event in the pre-event state. As the extreme event unfolds in the degradation state, resourcefulness indicates that mitigation plans and corrective actions are executed to alleviate the impact of damages. Rapid recovery means the system can be restored to normal conditions as fast as possible in the restoration state. Finally, adaptability ensures that lessons are well-learned and the system is enhanced against similar events in the post-event state.

To enhance the resilience of the electrical distribution system, an improved resilience trapezoid is shown in Fig. 2*b*. As shown, the resilience could be improved from four aspects, corresponding to the four vertices of the improved resilience trapezoid. First, the top-left vertex is shifted to the right (i.e. the start time of the degradation state is postponed from t_E to t'_E). This could be achieved by enhancing the robustness of the system, such as hardening the infrastructure and improving system redundancy. Second, the bottom left vertex is shifted up and to the left (i.e. the degradation state is ended early from t_D to t'_D), and the extent of the damage is reduced. This effect could result from timely mitigation plans and corrective actions. Third, the bottom right vertex is shifted up and to the left (i.e. the duration of the degraded state is shorted). Improving the system's situational awareness and damage assessment and keeping spare parts and repair crews on standby could lead to this result. Fourth, the top-right vertex is shifted to the left (i.e. the system is restored to the normal condition ahead of time). An optimal restoration plan that perfectly coordinates the repair crew, spare parts, transportation, and temporary power supply could accelerate the restoration process, leading to an early resumption of the interrupted normal condition.

The four aforementioned aspects of enhancing resilience can be further extracted into two key abilities enabling resilience: the ability of the system to withstand all kinds of extreme events and the ability to restore the system back to normal conditions with fast and efficient restoration measures. Considering the low probability of extreme events, the latter ability is more practical. A microgrid is a group of interconnected DGs, ESSs, and collocated loads with the ability to seamlessly disconnect from the utility grid and continue to operate as an islanded system. This feature of microgrids leads to lower probability and a lower amount of load shedding, which reduces the extent of cascading blackouts and time to restoration. Thus, DG and microgrids are critical for enhancing electrical distribution system resilience.

2.2 Quantifying metrics of resilience

Establishing specific and standardised metrics for evaluating and assessing resilience in the context of an electrical distribution system is particularly important and urgently needed. Only with these metrics can the weakness of the distribution system in the face of extreme events be identified, the strategies to enhance the resilience of the system are designed, and the related cost and associated benefits of resilience improvement be balanced. Due to the research on electrical distribution system resilience is still at an early state, there is no standard or widely recognised metric for quantifying the resilience in electrical distribution. Nevertheless, some efforts have been in progress [15–17].

As a pioneering effort in this area, Watson *et al.* [18] present a clear guideline towards a practical metric system of energy infrastructure. An appropriate metric system should be useful for decision-making, provide a mechanism for comparison, be usable in the contexts of planning and operation, exhibit expendability for different timescales and situations, be qualitative and quantitative, reflect uncertainty, support risk-based approaches, and capture system recovery time. In particular, quantitative metrics could be directly used to assess the effectiveness of various resilience enhancements or compare the resilience levels of different system configurations or situations. Therefore, quantitative metrics are more helpful than qualitative measures. Only quantitative metrics are discussed in this paper.

Although the standard definitions and metrics of resilience do not exist, the traditional reliability metrics have been directly used or modified to assess system resilience and compare difference measures for enhancing system resilience. In Panteli and Mancarella [19], the loss of load frequency and loss of load expectation are used to estimate the impact of weather on the frequency and duration of power interruptions. In Liu *et al.* [20], four different metrics are proposed to quantify the system

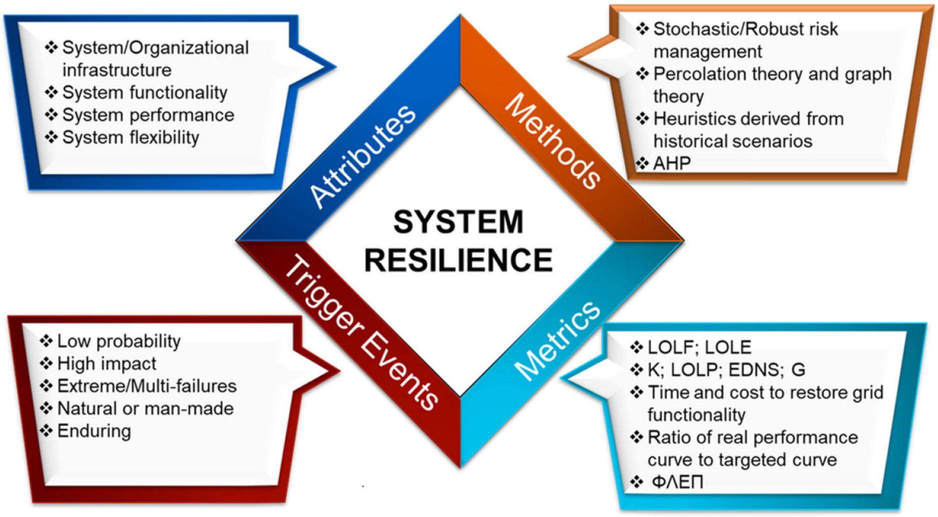

Fig. 3 *Conceptual framework of resilience in the context of an electrical distribution system*

resilience under extreme events: the expected number of lines on an outage (K), loss of load probability (LOLP), expected demand not served (EDNS), and difficulty level of grid recovery (G). Specifically, K quantifies the total number of lines on an outage due to an extreme weather event, LOLP quantifies the probability of the load not being supplied properly, EDNS quantifies the expected demand that the system is unable to supply, and G quantifies the severity of extreme events, infrastructure damage, and an inaccessible level of resources. Similarly, in Hosseini *et al.* [21], six metrics are proposed to quantify the various impacts of automated fault location, isolation, and service restoration on the resilience of electrical distribution systems after an extreme event: the expected maximum load loss, expected load interruption rate, expected automatic restoration time, expected load restored by automation, expected repair time, and expected energy not served.

To calculate these metrics, analytical methods based on the probabilistic assumptions on the occurrence and development of extreme events and the process and extent of components' damages are usually used. These probabilistic assumptions could be obtained through historical data analysis and prediction of future trends. Stochastic or robust scheduling methods have been used by distribution system operators to determine the optimal trade-off between the costs associated with customer service interruption and the costs of enhancing the distribution grid to avoid the customer service interruption or have been used to determine the most cost-effective measures for enhancing resilience under given resilience metrics.

To capture the temporal and uncertain nature of system performance during extreme events, some innovative resilience metrics were proposed in recent years. Francis and Bekera [22] propose a new resilience metric that considers recovery speed and system performance before and after the recovery. The damaged and restored states of the system are normalised to a stable state. Similarly, the resilience metric proposed in Henry and Emmanuel Ramirez-Marquez [23] is based on the difference of grid functionality between the degraded state and the pre-event state. However, the recovery speed has been neglected. In Panteli *et al.* [24], the $\Phi\Lambda E\Pi$ resilience metrics are proposed to indicate the speed (Φ) and magnitude (Λ) of the damaged grid functionality, the duration of the damaged state (E), and the recovery speed (Π). In Kwasinski [25], four metrics of resilience that correspond to the four main features of resilience summarised by the US NIAC are demonstrated: withstanding capability, recovery speed, preparation capability, and adaption capability. In Ouyang *et al.* [26], system resilience is assessed as the ratio of the real performance curve to the targeted performance curve. Another group of resilience metrics that use percolation theory and graph theory is proposed in Chanda and Srivastava [27]. The analytical hierarchical process is used to build a composite metric for the electrical distribution system. The Grid Modernization Laboratory Consortium, which is supported by the US Department of Energy, also proposed example resilience metrics that highlight the load priorities and statistical nature of uncertainty [28].

Although these novel resilience metrics demonstrate significant advantages over the modified reliability metrics by capturing the temporal nature of system performance under various extreme events – such as the speed and the magnitude of the damaged grid functionality, duration of the degraded state, and restoration speed, which corresponds to the four sides of the resilience trapezoid – there is still a common issue with these novel resilience metrics proposed by researchers. Currently, the application of these resilience metrics is limited to specific scenarios or situations. To standardise the resilience metrics, these metrics must be validated under all possible scenarios or situations.

The concept of resilience in the context of the electrical distribution system is summarised in Fig. 3. As shown, the summarised conceptual framework provides the necessary information and procedures for assessing electrical distribution system resilience. The summarised framework has four main aspects: trigger events, system attributes, evaluation methods, and metrics. First, trigger events identify the critical characteristics of scenarios or events that one should watch for when accessing electrical distribution system resilience. Second, attributes include the characteristics of an electrical distribution system, which might be affected by the trigger events. Next, metrics categorise the indices and indicators for evaluating and assessing resilience in the context of the electrical distribution system. Finally, methods present models and methodologies to evaluate the resilience metrics and compare the strategies to enhance electrical distribution system resilience.

3 Enhancing resilience

A resilience enhancement cycle is used to illustrate the general process of resilience assessment and enhancement in an electrical distribution system. As shown in Fig. 4, the resilience enhancement cycle has seven steps. The resilience enhancement begins with an extreme event modelling, which characterises the extreme event based on its type, magnitude, spatial and temporal attributes, and so on. The historical data from meteorological departments or weather institutions should be especially important for this step. Component functionality and health will be affected by an extreme event. This analysis is performed in the step of component vulnerability analysis at which the functionality of each component is evaluated along with the event progression. Then, electrical distribution system functionality is evaluated as the event unfolds (i.e. system degradation process). In this step, the mitigation plans and corrective actions that respond to ongoing disruptions should be considered. Subsequently, the system restoration is launched to restore the system functionality to the pre-event state. Both system automatic response and orders of operators should be considered in this step. As the system restoration ends, the resilience metrics are

Fig. 4 *Resilience enhancement cycle*

Table 2 Long-term measures for enhancing electrical distribution system resilience

Main aspects	Measures	References
improving component reliability	vegetation management	[29–31]
	undergrounding distribution lines	[32, 33]
	upgrading towers and poles with stronger materials	[34, 35]
	relocating/elevating substations	[36]
improving system resourcefulness	installing energy storage and DG	[37–40]
	deploying microgrids/ networked microgrids	[41–43]
	building redundant transmission and distribution lines	[44]
	establishing extended mutual aid agreements	[45]
improving system observability	improving visualisation and situation awareness	[46, 47]
	deploying dedicated fibre-optic reliable and interoperable communication networks	[48]
	improving extreme weather forecast and damage estimation	[49, 50]
improving system controllability	placing RCS	[51–53]
	deploying decentralised control	[54]
	demand-side management	[55, 56]
	using adaptive wide-area protection and control schemes	[57, 58]
	installing solid-state transformers	[59]

calculated. Afterwards, the resilience enhancement measures are compared and prioritised. Following the last step in which the optimal resilience enhancement measure is applied to the system, a new iteration of resilience assessment and enhancement continues.

As mentioned in Section 1, the measures to enhance electrical distribution system resilience can be categorised into two groups: long-term measures and short-term measures. The long-term measures usually refer to the planning and design of the electrical distribution system (i.e. a long-term decision-making paradigm). On the other hand, the short-term measures, essentially the operational measures, typically refer to the capability of the distribution system to mitigate the impacts of damages and restore the electricity supply to customers by using available resources and assets. Generally, the effectiveness of short-term measures to enhance resilience depends on the system's resourcefulness, observability, and controllability, which are usually improved through long-term enhancing measures.

3.1 Long-term measures

Long-term measures to enhance the resilience of the electrical distribution system mainly focus on four aspects: improving component reliability, system resourcefulness, system observability, and system controllability. First, enhancing component reliability could help reduce the damages, decrease the magnitude of the impacts, and accelerate restoration speed. These effects finally lead to improvements in electrical distribution system resilience. Second, resource redundancy can also enhance resilience by reducing the damages and decreasing the magnitude of the impacts. Third, observability and situational awareness are necessary for electrical distribution system restoration. Lacking observability or having bad situational awareness could lead to restoration failure. Finally, additional system controllability can decrease the magnitude of the impacts and accelerate restoration speed, improving resilience. The long-term measures for enhancing electrical distribution system resilience are summarised in Table 2.

3.1.1 Improving component reliability: Vegetation management is one of the most important aspects affecting the resilience of an electrical distribution system. Trees and bushes near the power conductors should be trimmed to a specified clearance to avoid possible contacts, which usually cause momentary or sustained interruptions. For example, the US-Canada blackout on 14 August 2003 started from short circuit faults caused by deficient vegetation management, deteriorated by inadequate situational awareness and contingency management, and resulted in cascading failures and widespread blackout [29]. A vegetation maintenance scheduling model for the electrical distribution system is proposed in Kuntz *et al.* [30]. A neural network model with a single-hidden layer is developed to forecast the failure rate of the overhead conductors. The problem is formulated as a combinatorial optimisation model and solved by a hybrid genetic algorithm hill-climbing technique. The solution determines when and where to perform vegetation maintenance and is subject to constraints on reliability, cost, and crew availability. The vegetation growth rates are considered to minimise the space between vegetation and energised conductors in Arias *et al.* [31]. Compared with overhead distribution conductors, underground distribution cables are less susceptible to natural disasters, thus reducing the impact of extreme events. In Kopsidas and Liu [32], the increased risk of failure and ageing that underground distribution lines experience during extreme events are considered when evaluating network resilience and system flexibility. An innovative model for planning a resilient underground distribution network based on geo-referenced data is proposed in Valenzuela *et al.* [33]. The optimal location of distribution transformers and medium voltage network routing are determined by using a minimum spanning tree algorithm.

Besides improving the reliability of distribution lines, electrical distribution system resilience could also be enhanced by upgrading towers and poles with stronger materials and relocating or elevating substations. Ma *et al.* [34] propose a tri-level optimisation model to minimise grid-hardening investment and load shedding in extreme weather events. The candidate hardening strategies include upgrading poles and vegetation management. However, DGs and system restoration have been ignored in the proposed model. In Lin and Bie [35], the tri-level optimisation is expanded to consider the operational resilience measures (i.e. DG islanding and network restoration). Additionally, relocating or elevating substations in low-lying areas can reduce the impact of storm surges and flooding during extreme weather events, as well as inherently enhance electrical distribution system resilience.

Innovative substation solutions and new technologies are proposed for system hardening to withstand storm and flooding in Boggess *et al.* [36].

3.1.2 Improving system resourcefulness: Electrical distribution system resilience could also be enhanced by improving the redundancy of resources, which would reduce the magnitude of the impacts and acceleration of the restoration process. Dong *et al.* [37] proposed an optimisation model for optimal sizing of ESS and backup generation considering the stochastic event occurrence time and duration. The stochastic features in the time window of optimisation are converted into a probability-weighted expression of load status. In [38], a two-stage robust optimisation model to coordinate the system hardening and DG placement with the objective of minimising the system damage under natural disasters is proposed. In particular, the spatial and temporal dynamics of an uncertain natural disaster are captured through an innovative multi-stage/multi-zone uncertainty set. Another DG sizing and siting approach considering both profits of DG owners and distribution companies with respect to the reliability of the electrical distribution system is proposed in [39]. An optimal sizing and siting scheme for the battery and PV, aiming at improving power system resilience is proposed in [40]. A new concept named capacity accessibility is proposed to quantify the system resilience during the extreme events. Microgrids at the customer or community level can be operated as a resilience resource to serve local loads, or critical loads outside the boundaries of the microgrid, even act as a black-start resource [41]. In [42], a mixed-integer linear programming (MILP) model for optimal microgrid design, i.e. optimal technology selection and allocation for multi-energy microgrids, is proposed. The electricity and heat transfer network constraints have been included in the optimisation formulation by linearised models. In fact, one of the most important benefits of networked microgrids is resilience enhancement. A resilient electrical distribution system design problem considering microgrid construction, system hardening, and additional line redundancy is proposed in [43]. The problem is formulated as a two-stage stochastic programming program and solved using scenario-based decomposition and a heuristic variable neighbourhood search. Generally, the integration of distributed energy resources and microgrids enhances grid resilience by increasing local generation capacity. Similarly, building redundant transmission and distribution lines could also boost the resilience of infrastructure by improving the system resistance to extreme and catastrophic events [44]. From the utility's point of view, as an initiative to improve grid resilience, many U.S. utilities have established extended mutual aid agreements on both spare parts and emergency repair crew to reduce the time of service restoration after extreme events [45].

3.1.3 Improving system observability: System observability and situational awareness are key factors for enhancing the resilience of the electrical distribution system, as they are prerequisite conditions for effectively and timely determining and executing mitigation and restoration strategies to an extreme event. Insufficient system observability and situation awareness usually result in a delayed or deficient response, even incorrect response leading to cascading events. In [46], the factors leading to insufficient situational awareness are identified. Then, measures for handling the problems related to situation awareness are discussed and their applicability to power systems is illustrated. In [47], a Markov model is proposed to quantify the impact of insufficient situation awareness on the probability and development of major incidents. The result of the case study clearly indicates that situation awareness is a key factor in preventing the propagation of an electrical failure. Deploying dedicated fibre-optic communication networks can significantly improve situational awareness, which benefits the grid resilience. According to the actual experience of Electric Power Board (EPB) of Chattanooga in the US [48], the fibre-optic communication system has provided benefits to practically every aspect of EPB' s operations in some way. In particular, EPB has seen significant improvements in its reliability metrics as a direct result of the fibre-optic communication system. In addition, the fibre-optic communication system provides the possibility of improving system observability through data-intensive technologies, e.g. phaser measurement units (PMUs). Another critical aspect of situational awareness is to predict the future state of system components based on their current state and the perceived information. In [49], a machine learning-based outage prediction model is proposed to determine the probable outage of power grid components in response to an imminent hurricane. The model is simple, fast, and robust. However, an extensive amount of data is needed to train the model in order to generate stable and meaningful results, compared to other prediction models, such as the support vector machine (SVM). A three-dimensional SVM is proposed to predict a component state in response to an upcoming hurricane in [50]. Still, an extensive amount of data is necessary for training the SVM.

3.1.4 Improving system controllability: The controllability of the system is another important factor affecting the resilience of an electrical distribution system, as it can decrease the magnitude of the impacts and accelerate the speed of restoration. The controllability of the electrical distribution system could be improved from many aspects, such as placement of remotely controlled switches (RCSs), deployment of a distributed control infrastructure, management of demand side, utilisation of intelligent or adaptive protection, installation of solid-state devices, etc. Upgrading manual switches to RCSs enhances restoration capability. In [51], the problem of optimal placement of RCSs is formulated as a weighted set cover (WSC) problem and solved by a greedy algorithm with a polynomial-time computational efficiency. In [52], a differential search algorithm is used to determine the optimum number and location of RCSs in a radial distribution feeder. However, the DGs have been neglected in [51, 52]. The effect of DGs on this problem is considered in [53]. The problem is solved as a two-level non-linear optimisation model and solved using a greedy algorithm. It should be noted that the existing restoration strategies are mostly based on centralised control architectures, which are also subject to damage or even breakdown caused by extreme events. To overcome this issue, a standards-based distributed architecture for electrical distribution system control is proposed in [54]. The utility and non-utility assets are coordinated by the proposed distributed architecture to increase reliability during normal operations and resiliency during extreme events. Another aspect of improving system controllability is to explore the flexibility provided by the demand side. In [55], a probabilistic optimisation model is proposed to minimise the network' s overhead lines ageing and maximise its reliability by leveraging the available demand response under emergency situations. In [56], it is demonstrated that the restoration of electrical distribution system could be significantly improved by integrated control of household-level flexible appliances. Additional system controllability can also be obtained from deployment of smart and intelligent wide-area protection and control schemes. Existing wide-area protection and control schemes are mostly pre-determined, which cannot handle the increasing complexity and uncertainty of power systems. With the deployment of advanced information and communication technology (ICT), smart and adaptive protection schemes capable to adapt to the evolving system conditions and dynamically determine the best course of action based on the unfolding events become possible and attractive [57]. A hierarchically coordinated protection (HCP) scheme is proposed to illustrate various approaches to corrective, adaptive and predictive protection actions aimed at improving power system resilience in [58]. The effectiveness of the proposed HCP scheme is validated by comparing it with legacy distance protection. Last but not least, solid-state transformer (SST) has been enabled by the advancements in power electronics, which enables new control capabilities and operation strategies towards a more resilient distribution grid. In [59], it is demonstrated that an SST-interconnected microgrid can become immune to disturbances that occur in the bulk power system, enabling robust and resilient power supply for its customers. Nevertheless, SST technology is

Table 3 Short-term measures for enhancing electrical distribution system resilience

Main aspects	Measures	References
prevention and preparedness	accurate estimation of location and severity of extreme events	[60–65]
	predictive risk analysis and component criticality ranking	[66–69]
	development and deployment of timely mitigation plan before and during the extreme events	[70–73]
reconfiguration and restoration	automatic restoration through topology reconfiguration	[74–80]
	repair crews dispatch	[81–83]

not yet widely accepted due to concerns about the reliability of itself.

3.2 Short-term measures

The short-term measures to enhance the resilience of the electrical distribution system are mainly focused on improving the operational capability, i.e. the ability of the electrical distribution system providing an electricity supply to customers under damaged conditions. Generally, the operational capability could be improved through two aspects: prevention and preparedness before the extreme events and conducting the repair and restoration of the distribution grid after the extreme events. In particular, DGs and microgrids can help in terms of both providing grid-forming capability and facilitating the restoration of the distribution grid due to its local resources and excellent controllability. The short-term measures for enhancing electrical distribution system resilience are summarised in Table 3.

3.2.1 Prevention and preparedness: Extreme event forecasting and tracking are some of the most important aspects of prevention and preparedness affecting the resilience of an electrical distribution system. Accurate estimation of location and severity of extreme events can help utilities make more specific and effective preparations. In the past decade, the development of computer science has promoted rapid progress in artificial intelligence (AI) technology, which is making its mark in weather prediction. In particular, airborne Doppler radar and satellite observations enable a rich training ground capable of feeding an AI system's endless appetite for data [60]. The Marshall Space Flight Center of National Aeronautics and Space Administration (NASA) has created a deep learning-based real-time hurricane intensity estimator [61]. To apply advanced deep learning technique at speed and scale, a cloud-based approach is designed to calculate hurricane strength and wind speed by monitoring live images from weather satellites. This allows NASA to create estimates up to every 30 s (a significant speedup from the traditional six-hour cycle), which drastically reduce the time to alert related authorities, such as utilities, to make possible mitigation efforts. A spatial data mining approach for heavy rainfall forecasting based on satellite image sequence analysis is proposed in [62]. In [63], a multi-layer neural network is proposed and trained to forecast the track of cyclones based on satellite images. The deep convolutional neural network (CNN) is employed to estimate the intensity of tropical cyclones based on satellite images in [64, 65]. It should be noted that AI systems estimate the tracks and intensity of hurricanes through mimicking human cloud pattern recognition. Thus, AI systems do not have a significant advantage in the accuracy of the prediction comparing with humans. Another issue is that AI systems cannot be used to predict long-term changing trends of natural disasters that are affected by climate change since they are trained using past records.

To predict the impacts of extreme events on the electrical distribution system, accurate forecasting and tracking of extreme events are necessary. Still, we need to build the fragility model for each kind of component, such as transformer, pole, and line. In [66], the fragility models of lines and towers are established for mapping the real-time impact of windstorms on their failure probabilities. A collection of the most accessible quantification methodologies for determining grid component vulnerability to climate and weather hazards (e.g. heatwave, windstorm, ice storm, flood) is summarised in [67]. It should be noted that certain components have more impacts on the resilience of the whole system to the extreme event that others. The enhancement of these critical components in advance can notably improve the resilience of the system facing the extreme event. In [68], a novel criticality assessment of system components under given resilience metrics is proposed. It is demonstrated that criticality ranking is a useful tool for component intervention prioritisation in the preventive phase. In [69], a component importance assessment approach of power systems for improving resilience under windstorms is proposed based on Monte Carlo simulation.

To achieve a fast and efficient emergency response, it is necessary for utilities to develop a mitigation plan beforehand, ensuring there are enough equipment and crews to quickly conduct the estimated repairs. The logistical deployment of resources to provide relief to disaster victims and the proactive planning of these activities are critical to cope with a sudden disaster, and thus attract many researchers and organisations [70]. However, the studies focused on disaster preparation in the context of electrical power system infrastructure are still limited. In [71], a proactive resource allocation model for repair and restoration of potential damages to the power system infrastructure located on the path of an upcoming hurricane is proposed. The model allows system operators to make a trade-off between the cost of repair resources allocation and the cost of load interruption. Depot location models to optimally store the resources needed for efficient and economic power restoration in the face of extreme events is proposed in [72, 73]. It should be noted that [71–73] all formulate the problem as stochastic mixed-integer programming, which could be efficiently solved by commercial solvers.

3.2.2 Reconfiguration and restoration: After the damages happen, it is the distribution system operator's top priority to restore the maximum interrupted loads within the minimum amount of time. Generally, this task could be divided into two steps. The first step is to restore electricity supply to critical customers by automatic topology reconfiguration of feeders through a series of switching operations, while the second step is to conduct the repair and restoration of the damaged parts of the grid with repair crews. Apparently, efficient reconfiguration and restoration strategy are critical for enhancing the resilience of the electrical distribution system. Precisely because of its importance, the automatic restoration of the distribution system through topology reconfiguration has been an active research area since the late last century [74, 75]. A decent number of algorithms have been proposed to address this large scale combinatorial problem, including heuristics [76], expert systems [77], meta-heuristics [78], mathematical programming [79], and multi-agent systems [80]. It should be noted that the topology reconfiguration utilises undamaged components to quickly restore electricity supply to customers by rerouting the power flows. Thus, its effectiveness depends on the observability and controllability of the distribution grid in the degraded state.

Restoration through the repair of the damaged parts basically consists of routing repair crews to fix damaged components and optimising the power flow. The problem was first investigated in [81]. By decoupling the routing and power flow model, a multistage program is proposed. In [82], a MILP combining the DC optimal power flow (OPF) problem with the vehicle routing problem (VRP) is formulated to dispatch repair crews to fix damaged components and restore the power supply. In [83], the repair crew dispatch problem is formulated as a MILP and heuristic model, separately. The computational performance of these two methods is compared. Nevertheless, an effective mitigation plan which allocates the resources and crew beforehand could improve the solution of the repair crew dispatch problem significantly.

4 Distributed generators (DGs) and microgrids in the context of grid resilience

Among various measures to enhance the resilience of the electrical distribution system, DGs and microgrids have emerged as a very promising candidate due to their ability of islanding and potential of sustaining the local generation to accelerate the restoration of the distribution system. Through islanding, the DGs and microgrids can disconnect from the faulty network and continue to supply the critical loads in the islanded portion with local DGs and ESSs before the restoration process starts. In essence, modern DGs and ESSs interfaced by converters present a higher controllability and operability degree than conventional generators. Particularly, the grid-forming converter can set the voltage amplitude and frequency of the local grid and maintain its stability by using a proper control loop.

Although resilience enhancement has been the most important key driver for microgrid deployment in recent years, the original purpose of the microgrid initiative is to coordinate the DGs in a decentralised way, thereby reducing the control burden of the grid and permitting DGs to provide their full benefits, such as increasing energy efficiency through combined heat and power (CHP) equipment, reducing carbon emissions, improving power quality and reliability (PQR) of end-users, and deferring grid expansion [84]. From the grid's perspective, a microgrid consists of a locally-controlled cluster of DGs and loads and behaves as a controllable entity electrically and in energy markets. In this way, electrical distribution systems with high DG penetration might not require significant operational and control capabilities. This could be clearly seen from the definition of microgrids by the U.S. Department of Energy, which defines a microgrid as a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that act as a single controllable entity with respect to the grid [85]. Similarly, the International Council on Large Electrical Systems (CIGRE) defines microgrids as electricity distribution systems containing loads and distributed energy resources that can be operated in a controlled, coordinated way either in grid-connected or islanded mode [86]. In line with the original purpose of the microgrid initiative, most earlier research efforts are focusing on the control and coordination of DGs to realise microgrid functions, including frequency and voltage control [87, 88], islanding and resynchronisation [89, 90], energy management [91–93], ancillary service [94–96], user interface and data management [97], etc. An overview of main operation modes and control structures for power converters in AC microgrids is presented in [98]. A reverse droop with virtual impedance (resistor) control is proposed and implemented in the grid-forming inverter of solar PV for the islanded PV-based microgrids in [99]. To improve the dynamic response of islanded microgrids, a grid-forming inverter controlled as a virtual synchronous generator is proposed in [100]. Besides, hierarchical microgrid controllers consisting of primary, second and tertiary controls are commonly used in the existing literature [101, 102].

One of the pivotal events in the history of microgrids is the superstorm Sandy, which hit the northeastern part of the US, including New York City, on 29 October 2012 [3]. The storm damaged or destroyed at least 650,000 homes, and 8 million customers lost power, including hospitals. However, it has been noticed that not everyone lost power. Microgrid operators, like Princeton University, showcased how microgrid technology kept the power on when the utility grid failed during the storm. This raised public awareness about the resilience of electricity supply and the advantages of microgrids in this particular respect. Historically, microgrid deployments could not be justified economically on their own merits. In the context of growing concern on grid resilience, this dilemma of microgrids may well be resolved by providing an environmental-friendly and reliable solution to enhance the resilience of electricity supply for end users. In line with the grid resilience initiative, recent research and development of microgrids are more focusing on the control systems and methods to ensure secure and robust islanding operation of microgrids during extreme events as well as strategies to assist the restoration of the electrical distribution system after extreme events.

Optimal island partition and microgrid formation can survive more critical loads and reduce the magnitude of the damaged grid functionality. A novel two-stage island partition model for the electrical distribution system with DGs is proposed in [103]. To survive critical loads from the power outages caused by natural disasters, a MILP model to form multiple microgrids energised by DGs from the radial distribution system is proposed in [104]. A resilient microgrid forming model considering master–slave DG operation and topology reconfiguration is proposed in [105]. Besides surviving critical loads by islanding, DGs and microgrids can also assist the restoration of the distribution system. Utilising DGs and microgrids to facilitate service restoration is reviewed in [106, 107]. Although these models and approaches provide precise, actionable measures targeted for reducing the impacts of extreme events and accelerating the restoration and recovery after extreme events, it should be noted that they do not encompass the various phases of resilience enhancement, as presented in Section 1.

Similar to Section 3, the DG and microgrid assisted measures to enhance the resilience of electrical distribution system can be investigated in four categories in terms of the time of events' occurrence, including resilience-oriented planning, resilience-oriented operation, emergency response, and restoration and recovery, as shown in Fig. 5. Resilience-oriented planning includes all long-term measures to improve the resilience of the electrical distribution system leveraging DGs and microgrids, such as system hardening, installation of DGs and ESS, and resilience-oriented design and deployment of microgrids. Resilience-oriented planning contains short-term measures to pre-position the location and operating state of DGs and microgrids against the coming extreme event, such as strategical placement of resources and preventive scheduling of DGs and microgrids. Different from resilient-oriented planning and operation measures, the emergency response refers to real-time operating strategies of DGs and microgrids during an extreme event, such as intentional/unintentional islanding and smart load shedding. At last, the system restoration and black-start measures leveraging DGs and microgrids fall into the category of restoration and recovery. Detailed strategies leveraging DGs and microgrids to enhance the resilience of the electrical distribution system are introduced and summarised in the following section.

5 DG and microgrid assisted resilience enhancement

The DG and microgrid assisted measures to enhance the resilience of electrical distribution system are mostly focused on improving the operational and recovery capabilities, i.e. the ability to resist the extreme events and maintain the electricity supply for critical loads during the events as well as facilitate the restoration process of the electrical distribution system after the events. In this section, strategies leveraging DGs and microgrids to enhance the resilience of the electrical distribution system are investigated in four categories, including resilience-oriented planning, resilience-oriented operation, emergency response, and restoration and recovery.

5.1 DG and ESS assisted resilience enhancement

In order to be differentiated from microgrids, the DGs and ESSs, in this section, mainly refer to distributed energy resources dedicated to supply critical/non-critical loads connected to the same bus in case of emergency. Thus, the constraints of the electric distribution network have been ignored when they are working in islanded mode. In addition, the coordination of multiple DGs and ESSs in both normal and emergency modes is realised through a distribution management system (DMS) rather than microgrid controller. The DG and ESS assisted measures for enhancing electrical distribution system resilience are summarised in Table 4.

5.1.1 Resilience-oriented planning of DGs and ESSs: Legacy emergency backup power supply based on diesel generator sets or

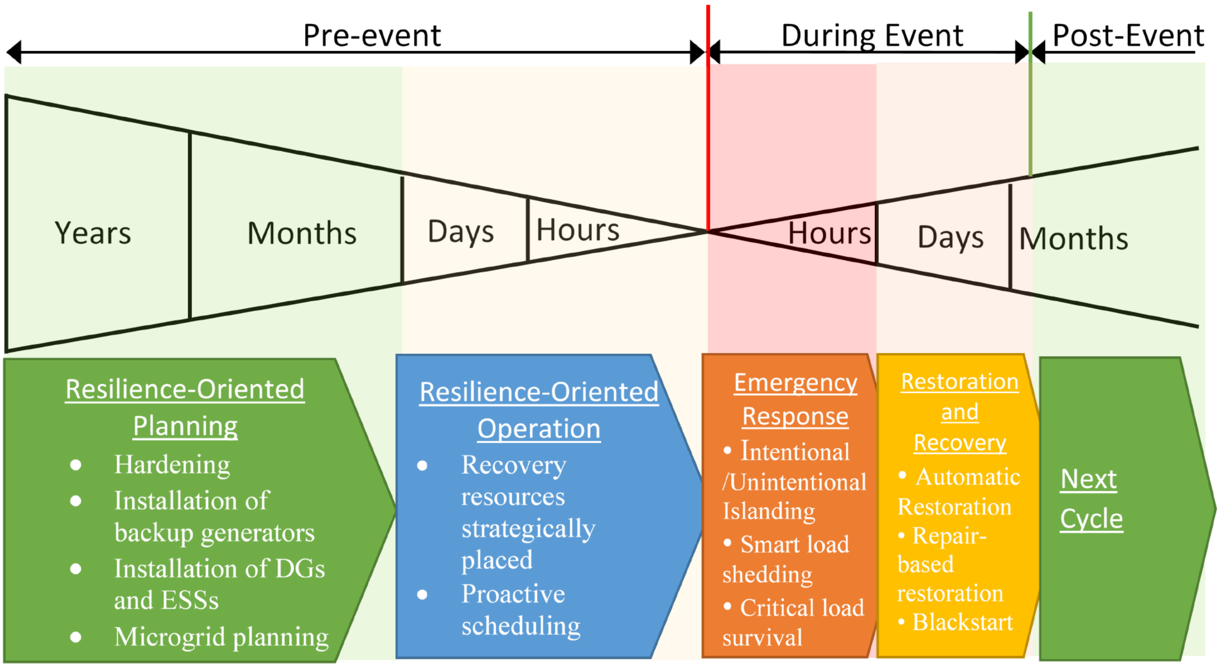

Fig. 5 *DG and microgrid assisted resilience enhancement in terms of the time of the event's occurrence*

Table 4 Electrical distribution system resilience enhancement leveraging DGs and ESSs

Main aspects	Measures	References
resilience-oriented planning	legacy emergency backup generators	[108–111]
	resilience-oriented siting and sizing of DGs and ESSs in electrical distribution network	[38, 112, 113]
resilience-oriented operation	strategical placement of mobile DGs and ESSs	[114, 115]
	proactive Scheduling of DGs and ESSs	[116, 117]
emergency response	grid-forming converter control	[98, 118, 119]
restoration and recovery	stationary grid-connected DGs and ESSs	[120–122]
	routing and scheduling of mobile DGs and ESSs	[123–125]

liquid propane/natural gas-powered generators has been installed in many facilities, such as commercial buildings, medical centres, military bases, etc. As a conventional method to restore power to critical customers in the case of distribution grid failures, these generators are typically configured to start automatically when a loss of power is sensed on the automatic switch. After the restoration of the distribution system, the backup generators automatically shut down and their fuel tanks are refilled. Backup generator sets are usually deployed as stand-alone generators tied to a single building. Compared with grid-connected DGs and ESSs, backup generator sets cannot realise the uninterrupted power supply for critical loads. However, due to its low investment and easy deployment, backup generator sets have been widely accepted as the best approach to improve the reliability of power supply for critical facilities [108]. In [109], the traditional backup generators sets and renewable energy-based microgrids for power resilience enhancement of a local clinic are compared from the techno-economic and environmental point of view. Simulation results indicate that PV-based microgrids have lower net present cost (NPC) and cost of energy (COE) for having almost the same resilience enhancement. Nevertheless, it is pointed out in [110] that the self-reliability of emergency backup diesel generators have significant impacts on the energy resiliency of critical loads. Poorly maintained emergency diesel generators might lead to a very high risk of power loss during grid outages. The value of a backup generator in terms of its contribution to the resilience improvement of a residential distribution network is quantified in [111]. In addition, the value of placing a backup generator at various distances from the substation, as well as the impacts of installing a large-scale backup generator versus several small-scale distributed backup generators are compared.

Unlike legacy diesel or liquid propane/natural gas-powered backup generator sets, modern DGs (e.g. PV) and ESSs (e.g. battery) are normally connected to the grid. Due to their advanced controllability, DGs and ESSs can realise the uninterrupted power supply for critical loads. To increase the resilience of an electric distribution system against extreme events, a resilient distribution network planning problem (RDNP) is proposed to minimise the total load shedding under natural disasters by coordinated system hardening and DG allocation in [38]. The problem is formulated as a two-stage robust optimisation model and solved using a decomposition algorithm. The feasibility of deploying ESSs in power distribution systems to improve its resilience against high-impact low-probability (HILP) incidents is investigated in [112]. A linear programming optimisation problem is formulated to determine the capacity and location of the ESSs for enhanced resilience against earthquakes. A very comprehensive DG for resilience planning guide is presented in [113]. Information and resources on how DG, with a focus on CHP, can help communities meet resilience goals and ensure critical infrastructure remains operational under extreme events are provided in the guide.

5.1.2 Resilience-oriented operation of DGs and ESSs: The strategical placement of DGs and ESSs in the context of resilience-oriented operation refers to mobile DGs and ESSs. Comparing with stationary DGs and ESSs, mobile or portable DGs and ESSs offer greater advantages and additional benefits to boost the resilience of the electrical distribution system since they could be deployed to the nearest and safest location based on the latest forecast of the coming extreme events. Before the extreme event happens, mobile DGs and ESSs should be pre-positioned in the electrical distribution system to enable uninterrupted power supply and rapid pre-restoration. In [114], a model for optimal allocation of mobile DGs to minimise the sum of mobile DG investment and maintenance cost as well as customers' outage cost is proposed. An optimised allocation of mobile emergency generators considering load priorities is proposed in [115]. The load shedding is minimised through a hierarchical dispatch strategy. It should be noted that the effectiveness of methods proposed in [114, 115] is quite limited due to lacking validated equipment damage models. Since the mobile DGs and ESSs are pre-positioned in staging locations for rapid real-time allocation after the extreme event, the placement decision of mobile DGs and ESSs should be made based on the damage forecasts of electrical distribution network and transportation network.

Beside mobile DGs and ESSs, the onsite DGs and ESSs should be proactively scheduled before the extreme event. As the utility grid outage is a high-probable threat after the disaster has hit, ESSs should be charged to a high state of charge (SOC). A resilience-constrained operation strategy is proposed in [116] using battery ESS (BESS) as a resilience resource. By formulating resiliency cuts for the SOC of BESS units in the pre-disturbance phase, the survivability of critical loads for n intervals after the occurrence of an extreme event is guaranteed. The proposed proactive operation strategy can significantly reduce the load shedding amount of critical loads during the extreme event. In [117], a resilience-oriented proactive scheduling methodology is proposed to enhance the preparedness of a multiple energy carrier distribution network against the approaching hurricane. Different from that of a single energy carrier distribution network, the contingency chain includes natural gas interruption, islanding event, and hurricane landfall on the multiple energy carrier distribution networks. Note that proactive scheduling of DGs and ESSs are mostly used to improve the probability of seamless islanding of microgrids. Thus, more literature on proactive scheduling of microgrids is reviewed in Section 5.2.2.

5.1.3 Emergency response of DGs and ESSs: To alleviate the cascading effects of extreme events and isolate more vulnerable components and customers in the electrical distribution network, self-adequate islands with DGs and ESSs are formed, thereby resilience is elevated. Grid-forming power converters are in charge of setting the voltage and frequency of the islands. A practical example of a grid-forming power converter is a standby uninterrupted power source (UPS). Once the utility power supply is interrupted, the UPS is automatically connected and the power converter of the UPS sets the grid voltage and frequency. In a microgrid, the voltage and frequency set by the grid-forming power converter will be used as a reference for the rest of grid-feeding power converters.

A detailed analysis of the main operation modes and control structures for power converters in a microgrid is presented in [98], focusing mainly on grid-forming, grid-feeding, and grid-supporting converters. The main control structure of a grid-forming power converter consists of two cascaded loops. The external loop is a voltage control loop in charge of regulating the output voltage, while the inner loop is a current control loop that regulates the current supplied by the power converter, tracking the reference current provided by the outer voltage loop. The grid-forming power converters can be controlled in both the dq synchronous and the $\alpha\beta$ stationary reference frames. A flexible control strategy for an 11-kW wind turbine with a back-to-back power converter capable of working in both stand-alone and grid-connection modes is proposed in [118]. The stand-alone control is featured with a complex output voltage controller capable of handling non-linear load and excess or deficit of generated power.

In essence, a grid-forming power converter emulates the behaviour of a swing source in the formed autonomous islands. The generation or storage units behind the converter should be adequately large and have adequate reserve capacity to mitigate the power unbalance. Due to limited capacities of DGs and ESSs in the electrical distribution system, two or more DGs or ESSs are commonly employed to regulate the voltage and frequency using frequency-droop and voltage-droop to share real and reactive power components [119]. To prevent overloading, the slope of each droop curve is usually set proportional to the rated capacity of the corresponding unit.

5.1.4 Restoration and recovery leveraging of DGs and ESSs: Besides maintaining the electricity supply for critical loads during emergency situations caused by extreme events, DGs and ESSs can also support temporary restoration while a full restoration may take a long period of time. A service restoration algorithm for balanced and unbalanced radial distribution networks considering DGs is proposed in [120]. In the proposed algorithm, DGs are only considered to be grid-following, and the grid-forming capability of DGs has been ignored. In [121], a new service restoration algorithm considering DGs' islanding is proposed. In addition, the impacts of vehicle-to-grid (V2G) facility and load priority are also investigated. In [122], a novel restoration strategy coordinating multiple sources, including microgrids, DGs, ESSs and other local resources to serve critical loads after blackouts is proposed. The unbalanced three-phase power flow is considered in the proposed model.

After the event happens, mobile DGs and ESSs could be dynamically dispatched in the distribution system to coordinate with other stationary DGs and ESSs as well as conventional restoration efforts. Therefore, both survivability and restoration of the system are enhanced. A two-stage optimisation model is proposed in [123] to utilise the spatial flexibility of transportable ESSs to bridge the gap between the economically optimal locations during normal operations and disaster-specific locations where extra back-up capacity will be needed. The proposed model is solved using a novel the progressive hedging algorithm. In [124], a joint restoration scheme considering transportable ESSs and DGs and traditional network reconfiguration is proposed. A temporal–spatial transportable ESS model, which is related to both transportation network and electrical distribution network, is formulated to differentiate the transportable ESSs from stationary ESSs in terms of flexibility and cost reduction of ESS sharing among microgrids. In [125], a novel mixed-integer programming model considering the coupling of road and power networks is formulated to optimise the dynamic dispatch of mobile power sources, including electric vehicle fleets, truck-mounted mobile ESSs, and mobile emergency generators against extreme weather events. It should be noted that the successful routing of transportable power resources is closely coupled with the resilience of the transportation network, which is also affected by the extreme events but rarely considered in the resilience enhancement of the electrical distribution system.

5.2 Microgrid assisted resilience enhancement

The recent development and deployment of microgrids have brought significant benefits to the electrical distribution system in the face of extreme events. Microgrids contribute to the improvement of resilience of the electrical distribution system in several aspects, from seamless defensive islanding to ensure security supply to critical customers to accelerating the restoration process of the electrical distribution system after the extreme event strikes. In particular, microgrids assisted restoration strategies have gained substantial traction in recent years. The microgrid assisted measures for enhancing electrical distribution system resilience are summarised in Table 5.

5.2.1 Resilience-oriented planning of microgrids: Strategies for long-term resilience-oriented planning of microgrids can be classified into three main categories: microgrid hardening, resilience-oriented microgrid planning, and deployment of smart grid technologies. Besides the system hardening measures previously mentioned in Section 3, there is one additional aspect, which should be considered for microgrid hardening, i.e. diversifying the generation sources [126]. The diversification of generation resources with various renewable energy sources reduces the microgrids' dependence on a single source of energy. For microgrids located on islands and remote places, diversification of generation resources with renewable energy sources and ESSs could reduce the risks associated with fuel transportation over long distances. This is important for the functionality of microgrids under the situation of extreme events since the transportation network is also very likely to be affected by extreme events.

Due to the importance of microgrids in protecting customers against extreme events and disasters, there has been extensive research on resilience-oriented microgrid planning. In [127], the

Table 5 Electrical distribution system resilience enhancement leveraging microgrids

Main aspects	Measures	References
resilience-oriented planning	microgrid hardening	[113, 126]
	resilience-oriented microgrid planning	[127–130]
	deployment of smart grid technologies	[131, 132]
resilience-oriented operation	proactive scheduling for seamless islanding and resynchronisation of microgrids	[133–143]
emergency response	optimal scheduling of islanded microgrids	[144, 145]
	smart load shedding	[146–149]
restoration and recovery	microgrids assisted restoration strategies	[106, 107, 150–155]
	microgrids assisted network formation strategies	[104, 129, 156–161]
	microgrids assisted blackstart	[162–164]

optimal planning of microgrids in the electric distribution system is formulated as a two-stage stochastic programming model. The investment plans, such as allocation of DGs and construction of new lines, are determined in the first stage, while the performance of potential solutions is assessed in the second stage against a set of damage scenarios sampled from a stochastic distribution. A scenario-based variable neighbourhood decomposition search (SBVNDS) is proposed to increase the solution efficiency. Robust optimisation-based microgrid planning is proposed in [128]. Comparing with stochastic optimisation-based approaches, the robust optimisation model only requires a deterministic uncertainty set, rather than a probability distribution of uncertain data, which is difficult to obtain in practice. Based on traditional N–k contingency analysis, a two-stage robust optimisation model considering the worst scenarios has been proposed in [129]. A tri-level robust microgrid planning model with a guaranteed resilience level is proposed in [130]. The resilience level of microgrids is quantified and maintained such that the load shedding is constrained within a given bound under any realisation of N–k contingencies.

Resilience enhancement measures leveraging DGs and microgrids, especially DG and microgrid assisted restoration and recovery, cannot be implemented without the deployment of smart grid techniques, such as advanced metering infrastructure (AMI), telecommunications, distribution/outage management system (DMS/OMS), automated demand response programs, etc. These technologies enhance the visibility and controllability of the electrical distribution system by enabling real-time situational awareness and remote control [131, 132]. It should be pointed out that the deployment of smart grid technologies might be more expensive and time-consuming comparing to the deployment of DGs and microgrids. However, precisely because of these smart grid techniques, DGs and microgrids could make a huge difference in the resilience enhancement of electrical distribution system against extreme events.

5.2.2 Resilience-oriented operation of microgrids: Microgrids, as physical defensive islands in a local area, could be formulated by assembling the adjacent DGs and ESSs to provide uninterrupted electricity supply to customers before the extreme event happens. More importantly, microgrids need to prepare for islanding before the extreme event strikes by scheduling their resources in a conservative way, i.e. proactive scheduling. Unsuccessful islanding may occur due to inadequate capacity for power-sharing, loss of synchronisation for grid-interactive inverters, and/or small-signal instability. Given these factors, the preventive scheduling of microgrids is essential for the resilience enhancement of the electrical distribution system.

Islanding capability under load and renewable uncertainty has been studied in [133–137]. In [133], a two-stage robust scheduling mode for microgrids considering islanding capability is proposed. In [134], considering the uncertainty of renewable generation and loads, the islanding constraint is represented as a chance constraint. In [135, 136], two-stage stochastic optimisation models are proposed for the proactive scheduling of microgrids considering unintentional islanding caused by extreme events. The formulated two-stage stochastic models are solved using Benders' decomposition. Benders' cuts are generated from the second stage subproblems and added to the first stage problem to avoid the infeasibility of the first stage problem. A resiliency-oriented stochastic linear programming approach for proactive scheduling of microgrids is developed in [137], which exploits conservation voltage regulation (CVR) as an energy resource for improving the resiliency of islanded microgrids. The key concern in these works is to have an adequate spinning reserve to ensure proper load sharing. The load shedding strategies have also been identified as an effective approach for the microgrid islanding transition. A robust strategy is proposed in [138].

It should be pointed out that [133–138] are all based on a steady-state analysis of the microgrids. The small-signal stability and transient stability have been neglected. The small-signal stability of islanded microgrids with respect to the system operating condition is investigated in [139]. The frequency response of droop-controlled inverters at steady state after islanding is considered in [140], where the droop control gains are co-optimised with other control commands. In [141], a further improvement by considering the dynamic frequency response constraint in addition to the steady state is proposed. Most studies employ a low-order frequency response model and piece-wise linearisation to encode the nonlinear frequency nadir expression into the mixed-integer programming model, which is shown to be accurate in synchronous generator-dominated bulk grids [142]. For microgrids with grid-interactive inverters, this approach is unable to incorporate responses from grid-interactive inverters, since there is no analytical expression for the step response of higher-order differential equations. In addition, other practical factors, such as phase-lock loop (PLL) transient, low-pass filters, dead-band, and saturation, could also alter the response and have not been considered yet. A deep learning aided constraint encoding approach is proposed in [143]. The complex map from system states and controls to the frequency nadir is first parameterised using a neural network, and then formulate the trained neural network into a MILP. Using machine learning algorithms to approximate the trajectory constraints in proactive scheduling of microgrids remains an area with huge research potential.

5.2.3 Emergency response of microgrids: After the transition from the grid-connected model to islanded mode with limited transients, microgrids still need to serve the critical loads in the islanded portion utilising local resources before the restoration is finished. Novel control strategies required to stabilise the frequency and voltage of islanded microgrids are evaluated in [144]. It is demonstrated that the forced islanding of the microgrids could be performed safely under several different power importing and exporting conditions. In addition, effective management of ESSs and load shedding are especially important to avoid fast and long frequency deviations. A hierarchical control strategy of a DC microgrid is proposed in [145] for both grid-connected operation and unplanned islanding of the DC microgrid.

Due to limited generation resources in microgrids, load shedding actions are usually unavoidable. A dynamic load shedding strategy is proposed in [146], which is formulated as a stochastic optimisation problem considering the uncertainties of intermittent energy sources and loads. A multi-level under frequency load shedding strategy for a stand-alone microgrid is designed and validated on a real microgrid testbed in [147]. Besides load shedding, the overload problem in an islanded microgrid during an extreme event can also be relieved by connecting neighbouring microgrids. In [148], a self-healing agent is developed to couple two islanded microgrids for better power-sharing. Different interconnection and isolation conditions have been derived. To handle the uncertainty of renewable generation and loads in microgrids, various models, such as stochastic programming, robust programming, chance-constrained programming, etc., have been investigated. The spinning reserve requirement of an islanded microgrid is estimated using a probabilistic methodology in [149]. The optimal spinning reserve requirement is determined by a tradeoff between reliability and economics.

5.2.4 Restoration and recovery leveraging microgrids: As unique generation resources located on the demand side, microgrids not only maintain robust electricity supply for critical loads during the extreme event. In fact, microgrids are playing a more and more important role in the restoration and recovery process of the electrical distribution system after the extreme event strikes. Strategies leveraging microgrids to facilitate the restoration and recovery of the electrical distribution system are investigated in three categories, including microgrid assisted restoration, microgrid assisted network formation, and microgrid assisted blackstart.

Microgrids assisted restoration: Microgrids could assist the distribution grid restoration by serving as additional power sources. As mentioned earlier, microgrid assisted service restoration of the electrical distribution system is reviewed in [106, 107]. More strategies of microgrids assisting electrical distribution system restoration with resilience enhancement as the objective are proposed in [150–154]. The feasibility of using microgrids for service restoration is demonstrated in [150]. The microgrid used for restoration is assumed to have no synchronous generators, but only electronic interfaced microgenerators and asynchronous generators. The results indicate that ESSs are absolutely essential during all restoration stages. A resilience-oriented service restoration model using microgrids to restore critical load after natural disasters is proposed in [151]. The service restoration model considers the uncertainty of renewable generation and load as well as constraints on service time.

It should be noted that the service restoration process is actually a sequence of control actions for switches, ESSs, and dispatchable DGs, which energise the system step by step. For each step, the operational constraints should not be violated. A resiliency-based methodology that uses microgrids to restore critical loads on distribution feeders after a major disaster is proposed in [152]. In particular, the proposed restoration model considers the stability of microgrids, limits on frequency deviation, and limits on transient voltage and current of DGs as constraints. A novel multi-step service restoration methodology for distribution system considering microgrids and cold load pickup is proposed in [153]. This work is further extended to consider the unbalanced distribution system in [154].

Microgrids assisted network formation: Microgrid could facilitate the network formation of the distribution system when the grid ties have been damaged. Under this situation, microgrids are leveraged through network reconfiguration to form islands so as to restore power to as more customers as possible. The microgrid assisted network formation strategies are investigated in [104], which propose a novel resilience enhancement based on the microgrid islanding and optimal reconfiguration of distribution network after extreme events. To improve the computational performance, the model proposed in [104] is reformulated with reduced the number of both binary and continuous variables in [156]. In [157], a novel comprehensive operation and self-healing strategy for a distribution system with DGs is proposed. The self-healing strategy is realised by optimally sectionalising the on-outage portion of the distribution system into self-supplied microgrids so as to provide a reliable power supply to the maximum loads continuously. A distribution level microgrid formation model considering high renewable penetration level and meshed topology is proposed in [129].

Neighbouring microgrids could be networked to support each other during major disruption events. Within networked microgrids, if the generation of a microgrid is damaged during the extreme event, other microgrids could help to pick up the critical loads of the compromised microgrid. In this way, the resilience of single microgrids could be further enhanced [158]. Networked microgrids facilitating service restoration after a severe event is presented in [159]. The self-healing function of the distribution system based on dynamic sectionalisation into microgrids is proposed in [160]. In the self-healing mode, a consensus algorithm is used to distribute the desired power support of on-emergency microgrid to other healthy microgrids in a decentralised way. Comparing with the centralised control method, this decentralised control method is robust to the partial damages of the communication infrastructure. Meanwhile, the privacy of each individual microgrid is preserved. A two-stage resilience enhancement strategy using networked microgrids is proposed in [161]. The power sharing among the microgrids is considered to enhance the survivability of critical loads in the second stage.

Microgrids assisted blackstart: Although microgrids normally have generation capacity <10 MW and are directly connected to the distribution system, microgrids have the potential to be used as black-start resources due to two advantages. First, microgrids have a high probability to survive an extreme event. Second, the advanced controllability of DGs and ESSs in microgrids makes them very flexible in terms of ramping rate, reactive power compensation, stability control, etc. A stochastic MILP model to assess the impact of coordinating microgrids as a black-start resource after a natural disaster is proposed in [162]. However, only steady-state variables are considered in this work.

In fact, modelling dynamic behaviours is necessary for designing a black-start scheme using microgrids since microgrids often need to energise long sections of transmission lines to reach a large power station. The feasibility of using microgrids as black-start resources in terms of frequency response, in-rush currents, and voltage response is analysed in [163]. The simulation results indicate that it is feasible for microgrids to act as black-start resources if the microgrid is located near or not far from a large power station. A model predictive control based generator startup strategy using microgrids as black-start resources is proposed in [164]. In particular, the uncertainties of the microgrid during the black-start process are modelled as representative scenarios based on the discretisation of the probability distribution of forecast errors. Note that the transients during the black-start process are not considered in the proposed model.

5.3 Resilience metrics and indices in the context of DGs and microgrids

The resilience metrics and indices commonly used to validate the effects of DGs and microgrids on enhancing the resilience of the electrical distribution system are summarised in Table 6. As can be seen, the most frequently used metrics to validate the effects of DGs and microgrids on resilience enhancement is the total prioritised loads restored after extreme events or involuntary load shedding after extreme events. To a large extent, this reflects the popularity of two-stage stochastic/robust models in existing literature, which usually determine the resilience enhancement strategies in the first stage, then assess the performance of candidates against a set of sampled damage scenarios in the second stage. Probabilistic metrics, such as the probability of a certain fraction of critical load served after events, are also popular in evaluating resilience enhancement strategies leveraging DGs and microgrids since they could be formulated as chance constraints, then included in the optimisation problem. The time feature of resilience starts to be captured by metrics, such as repair time and average time of load unserved. However, more research is still needed in this aspect.

6 Future research

Based on the review of the existing literature on electrical distribution system resilience definitions, characteristics, and enhancement measures, the recommendations for future research are listed as follows:

(i) The standard definition of resilience in an electrical distribution system is still an urgent need. Using different definitions of resilience, the resulted resilience enhancement measures might be

Table 6 Resilience metrics and indices used to validate the effects of DGs and microgrids on resilience enhancement

Resilience metrics/indices	References
K, LOLP, EDNS, G	[20]
SAIDI, CAIDI, ENS	[111]
probability of having electricity continuously available during a power outage	[109]
probability of a certain fraction of critical load served after events	[127]
probability of successful islanding of microgrids	[133–136]
topological resiliency vector $\mathscr{R}_\tau$	[26]
preparedness index	[117]
total prioritised loads restored after events	[104, 105, 120–122, 129, 150–154, 156]
involuntary load shedding after events	[38, 112, 116, 130, 146–149]
outage cost of customers	[114, 115, 123, 124, 137, 140, 141]
worst-case weighted sum of survived loads	[125]
total picked-up loads and the repair time of the damaged components	[155]
average time that load is unserved	[162]

vastly different, which might mislead the investment strategy of the stakeholder or policymakers.

(ii) Standard or widely-accepted quantitative indices of resilience are another need. Note that the quantification of electrical distribution system resilience requires more than a single index considering the need to evaluate both the magnitude of grid functionality and the recovery speed.

(iii) The business models of microgrids assisted resilience enhancement are not well-established. This leads to significant financial risks for stakeholders. The long-term measures to enhance the resilience of the electrical distribution system are also facing this issue.

(iv) The optimisation models for selecting optimal resilience enhancement measures under a limited budget and time should be developed. These models should be flexible enough to consider the stakeholder' preferences and support their customised decision-making process.

(v) The microgrid assisted restoration and network formation strategies are still focused on the steady-state analysis. The transients during islanding, cold load pick up, and blackstart are rarely considered. Through parameterising the dynamic response and transients and directly incorporating the transient constraints into microgrid assisted restoration and network formation strategies, the violations of system constraints during the transient process could be avoided. Further research is needed in this area.

(vi) The interdependency among electrical distribution system, heating/cooling distribution system, natural gas distribution system, traffic system as well as communication system should be modelled and considered in a realistic resilience enhancement analysis. In particularly, research on microgrid assisted restoration and network formation strategies with partially or completely damaged communication systems have great practical significance.

(vii) There are many legal and regulatory issues standing in the way of DGs and microgrids assisting resilience enhancement. For example, utilities currently do not allow customers back-feeding power into the grid during an outage. New business models of DGs and microgrids reflecting resiliency benefits need to be built.

7 Conclusions

In this paper, an extensive review of the state-of-the-art research on electrical distribution system resilience is presented. Definitions, characteristics, differences from reliability, and quantifying metrics of resilience are discussed. Various measures to enhance resilience in the context of an electrical distribution system have been reviewed and compared. In particular, the functions of microgrids in enhancing the distribution system resilience, such as defensive islanding, service restoration, and network formation, are investigated. In addition, recommendations for future research are presented.

8 Acknowledgments

This work was supported by the U.S. Department of Energy's Office of Electricity Delivery and Energy Reliability (OE) under contract no. DE-AC05-00OR22725. The authors also thank the support in part by the National Natural Science Foundation of China (grant no. 51877033, 51607033, 52061635103, and 51677023), the National Key Research and Development Program of China (2016YFB0900903), and the International Clear Energy Talent Program (iCET) of China Scholarship Council. This work also made use of Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and the Department of Energy under the National Science Foundation Award Number EEC-1041877 and the CURENT Industry Partnership Program.

This manuscript has been authored by UT-Battelle, LLC under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the article for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

9 References

[1] Georgilakis, P.S., Hatziargyriou, N.D.: 'A review of power distribution planning in the modern powers systems era: models, methods and future research', *Electr. Power Syst. Res.*, 2015, **121**, pp. 89–100

[2] Brown, H.E., Suryanarayanan, S., Natarajan, S.A., *et al.*: 'Improving reliability of islanded distribution systems with distributed renewable energy resources', *IEEE Trans. Smart Grid*, 2012, **3**, (4), pp. 2028–2038

[3] U.S. Department of Commerce (US DoC): 'Economic Impact of Hurricane Sandy', Potential Economic Activity Lost and Gained in New Jersey and New York', USA, 2013

[4] Zhou, B., Gu, L., Ding, Y., *et al.*: 'The great 2008 Chinese ice storm: its socioeconomic-ecological impact and sustainability lessons learned', *Bull. Am. Meteorol. Soc.*, 2014, **92**, (1), pp. 47–60

[5] Coffey, B., Stern, A., Wing, I.S.: 'Climate change impacts on U.S. electricity demand: Insights from micro-consistent aggregation of a structural model', Tech. Paper, Univ. South Carolina, Columbia, SC, USA, 2015

[6] Executive Order of the President: 'Council of economic advisers, economic benefits of increasing electric grid resilience to weather outages', The Council, 2013

[7] Kenward, A., Raja, U.: '*Blackout: extreme weather, climate change and power outages*' (Princeton, NJ, 2014)

[8] PJM: 'PJM's evolving resource mix and system reliability', 2017

[9] IEEE PES Industry Technical Support Task Force: 'The definition and quantification of resilience', IEEE, 2018, pp. 1–3

[10] CERTS Microgrid Concept: 2003, Available at: http://certs.lbl.gov/certs-der-micro.html

[11] Katiraei, F., Iravani, M.R., Lehn, P.W.: 'Micro-grid autonomous operation during and subsequent to islanding process', *IEEE Trans. Power Deliv.*, 2005, **20**, (1), pp. 248–257

[12] Hirsch, A., Parag, Y., Guerrero, J.: 'Microgrids: a review of technologies, key drivers, and outstanding issues', *Renew. Sustain. Energy Rev.*, 2018, **90**, pp. 402–411

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

[14] Berkeley, A., Wallace, M.: 'A framework for establishing critical infrastructure resilience goals: final goals and recommendations', National Infrastructure Advisory Council (NIAC), 2010

[15] Bie, Z., Lin, Y., Li, G., *et al.*: 'Battling the extreme: a study on the power system resilience', *IEEE Proc.*, 2017, **105**, (7), pp. 1253–1266

[16] Lin, Y., Bie, Z.: 'Study on the resilience of the integrated energy system', *Energy Proc.*, 2016, **103**, pp. 171–176

[17] Rickerson, W., Gillis, J., Bulkeley, M.: 'The value of resilience for distributed energy resources: an overview of current analytical practices'. NARUC, Washington, DC, 2019

[18] Watson, J.P., Guttromson, R., Silva-monroy, C., *et al.*: 'Conceptual framework for developing resilience metrics for the electricity, oil, and gas sectors in the United States', New Mexico, 2014

[19] Panteli, M., Mancarella, P.: 'Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events', *IEEE Syst. J.*, 2017, **11**, (3), pp. 1733–1742
[20] Liu, X., Shahidehpour, M., Li, Z., *et al.*: 'Microgrids for enhancing the power grid resilience in extreme conditions', *IEEE Trans. Smart Grid*, 2017, **8**, (2), pp. 589–597
[21] Hosseini, M., Umunnakwe, A., Parvania, M.: 'Automated switching operation for resilience enhancement of distribution systems'. 2019 IEEE PES General Meeting, Atlanta, GA, USA, 2019, pp. 1–5
[22] Francis, R., Bekera, B.: 'A metric and frameworks for resilience analysis of engineered and infrastructure systems', *Reliab. Eng. Syst. Saf.*, 2014, **121**, pp. 90–103
[23] Henry, D., Emmanuel Ramirez-Marquez, J.: 'Generic metrics and quantitative approaches for system resilience as a function of time', *Reliab. Eng. Syst. Saf.*, 2012, **99**, pp. 114–122
[24] Panteli, M., Mancarella, P., Trakas, D.N., *et al.*: 'Metrics and quantification of operational and infrastructure resilience in power systems', *IEEE Trans. Power Syst.*, 2017, **32**, (6), pp. 4732–4742
[25] Kwasinski, A.: 'Quantitative model and metrics of electrical grids resilience evaluated at a power distribution level', *Energies*, 2016, **9**, p. 93
[26] Ouyang, M., Duenas-Osorio, L., Min, X.: 'A three-stage resilience analysis framework for urban infrastructure systems', *Struct. Saf.*, 2012, **36**, pp. 23–31
[27] Chanda, S., Srivastava, A.K.: 'Defining and enabling resiliency of electric distribution systems with multiple microgrids', *IEEE Trans. Smart Grid*, 2016, **7**, (6), pp. 2859–2868
[28] Foundational Metrics Analysis. Grid Modernization Laboratory Consortium (GMLC), May 2017
[29] Gholami, A., Member, S., Shekari, T., *et al.*: 'Toward a consensus on the definition and taxonomy of power system resilience', *IEEE Access*, 2018, **6**, pp. 32035–32053
[30] Kuntz, P.A., Christie, R.D., Venkata, S.S.: 'Optimal vegetation maintenance scheduling of overhead electric power distribution systems', *IEEE Trans. Power Deliv.*, 2002, **17**, (4), pp. 1164–1169
[31] Arias, L.A., Hincapie, R.A., Granada, E.M.: 'Integrated methodology between metaheuristic techniques for optimal vegetation maintenance in distribution systems'. 2014 IEEE PES T&D Conf. Expo., Chicago, IL, USA, 2014, pp. 1–5
[32] Kopsidas, K., Liu, S.: 'Power network reliability framework for integrating cable design and ageing', *IEEE Trans. Power Syst.*, 2018, **33**, (2), pp. 1521–1532
[33] Valenzuela, A., Inga, E., Simani, S.: 'Planning of a resilient underground distribution network using georeferenced data', *Energies*, 2019, **12**, p. 644
[34] Ma, S., Chen, B., Wang, Z.: 'Resilience enhancement strategy for distribution systems under extreme weather events', *IEEE Trans. Smart Grid*, 2018, **9**, (2), pp. 1442–1451
[35] Lin, Y., Bie, Z.: 'Tri-level optimal hardening plan for a resilient distribution system considering reconfiguration and DG islanding', *Appl. Energy*, 2018, **210**, pp. 1266–1279
[36] Boggess, J.M., Becker, G.W., Mitchell, M.K.: 'Storm & flood hardening of electrical substations'. 2014 IEEE PES T&D Conf. Expo., Chicago, IL, USA, 2014, pp. 1–5
[37] Dong, J., Zhu, L., Su, Y., *et al.*: 'Battery and backup generator sizing for a resilient microgrid under stochastic extreme events', *IET Gener. Transm. Distrib.*, 2016, **12**, (20), pp. 4443–4450
[38] Yuan, W., Wang, J., Qiu, F., *et al.*: 'Robust optimization-based resilient distribution network planning against natural disasters', *IEEE Trans. Smart Grid*, 2016, **7**, (6), pp. 2817–2826
[39] Hasanvand, S., Nayeripour, M., Khooban, M.H., *et al.*: 'Power system distribution planning considering reliability and DG owner's profit', *J. Renew. Sustain. Energy*, 2017, **9**, (6), p. 065508
[40] Zhang, B., Dehghanian, P., Kezunovic, M.: 'Optimal allocation of PV generation and battery storage for enhanced resilience', *IEEE Trans. Smart Grid*, 2019, **10**, (1), pp. 535–545
[41] Ton, D., Wang, P.: 'A more resilient grid', *IEEE Power Energy Mag.*, 2015, **13**, pp. 26–34
[42] Salman, M., Stadler, M., Cardoso, G., *et al.*: 'A mixed integer linear programming approach for optimal DER portfolio, sizing, and placement in multi-energy microgrids', *Appl. Energy*, 2016, **187**, pp. 154–168
[43] Barnes, A.K., Harsha, N., Emre, Y., *et al.*: 'Tools for improving resilience of electric distribution systems with networked microgrids', ArXiv abs/1705.08229, 2017
[44] Panteli, M., Trakas, D.N., Mancarella, P., *et al.*: 'Power systems resilience assessment: hardening and smart operational enhancement strategies', *Proc. IEEE*, 2017, **105**, (7), pp. 1202–1213
[45] Arghandeh, R., Brown, M., Del Rosso, A., *et al.*: 'The local team: leveraging distributed resources to improve resilience', *IEEE Power Energy Mag.*, 2014, **12**, (5), pp. 76–83
[46] Panteli, M., Kirschen, D.S., Crossley, P.A., *et al.*: 'Enhancing situation awareness in power system control centers'. IEEE Int. Multi-Disciplinary Conf. on Cognitive Methods in Situation Awareness and Decision Support, San Diego, CA, USA, 2013, pp. 254–261
[47] Panteli, M., Crossley, P.A., Kirschen, D.S., *et al.*: 'Assessing the impact of insufficient situation awareness on power system operation', *IEEE Trans. Power Syst.*, 2013, **28**, (3), pp. 2967–2977
[48] Starke, M., Ollis, B., Glass, J., *et al.*: 'Analysis of Electric Power Board of Chattanooga Smart Grid Investment', United States, 2017
[49] Eskandarpour, R., Khodaei, A.: 'Machine learning based power grid outage prediction in response to extreme events', *IEEE Trans. Power Syst.*, 2017, **32**, (4), pp. 3315–3316
[50] Eskandarpour, R., Khodaei, A., Arab, A.: 'Improving power grid resilience through predictive outage estimation'. NAPS 2017 – 49th North American Power Symp., Proc., Morgantown, WV, USA, 2017, pp. 1–5
[51] Xu, Y., Liu, C.C., Schneider, K.P., *et al.*: 'Placement of remote-controlled switches to enhance distribution system restoration capability', *IEEE Trans. Power Syst.*, 2016, **31**, (2), pp. 1139–1150
[52] Ray, S., Bhattacharjee, S., Bhattacharya, A.: 'Optimal allocation of remote control switches in radial distribution network for reliability improvement', *Ain Shams Eng. J.*, 2018, **9**, (3), pp. 403–414
[53] Isapour Chehardeh, M., Hatziadoniu, C.J.: 'Optimal placement of remote-controlled switches in distribution networks in the presence of distributed generators', *Energies*, 2019, **12**, p. 1025
[54] Schneider, K.P., Laval, S., Hansen, J., *et al.*: 'A distributed power system control architecture for improved distribution system resiliency', *IEEE Access*, 2019, **7**, pp. 9957–9970
[55] Kopsidas, K., Abogaleela, M.: 'Utilizing demand response to improve network reliability and ageing resilience', *IEEE Trans. Power Syst.*, 2019, **34**, (3), pp. 2216–2227
[56] Hafiz, F., Chen, B., Chen, C., *et al.*: 'Utilising demand response for distribution service restoration to achieve grid resiliency against natural disasters', *IET Gener. Transm. Distrib.*, 2019, **13**, (4), pp. 2942–2950
[57] Panteli, M., Mancarella, P.: 'The grid: stronger, bigger, smarter?: presenting a conceptual framework of power system resilience', *IEEE Power Energy Mag.*, 2015, **13**, (3), pp. 58–66
[58] Tasdighi, M., Kezunovic, M.: 'Hierarchically coordinated protection: a key element in improving power system resilience'. 2018 IEEE Int. Energy Conf. (ENERGYCON), Limassol, 2018, pp. 1–6
[59] Sanduleac, M., Martins, J.F., Ciornei, I., *et al.*: 'Resilient and immune by design microgrids using solid state transformers', *Energies*, 2018, **11**, p. 3377
[60] Zhang, F., Weng, Y.: 'Predicting hurricane intensity and associated hazards: a five-year real-time forecast experiment with assimilation of airborne Doppler radar observations', *Bull. Am. Meteorol. Soc.*, 2015, **96**, (1), pp. 25–33
[61] The Deep Learning-based Hurricane Intensity Estimator: 2020, Available at http://hurricane.dsig.net/
[62] Yang, Y., Lin, H., Gao, Z., *et al.*: 'A data mining approach for heavy rainfall forecasting based on satellite image sequence analysis', *Comput. Geosci.*, 2007, **33**, (1), pp. 20–30
[63] Kovordanyi, R., Roy, C.: 'Cyclone track forecasting based on satellite images using artificial neural networks', *ISPRS J. Photogramm. Remote Sens.*, 2009, **64**, (6), pp. 513–521
[64] Pradhan, R., Aygun, R., Maskey, M., *et al.*: 'Tropical cyclone intensity estimation using a deep convolutional neural network', *IEEE Trans. Image Process.*, 2018, **27**, (2), pp. 692–702
[65] Lee, J., Im, J., Cha, D., *et al.*: 'Tropical cyclone intensity estimation using multi-dimensional convolutional neural networks from geostationary satellite data', *Remote Sens.*, 2020, **12**, p. 108
[66] Panteli, M., Pickering, M., Wilkinson, S., *et al.*: 'Power system resilience to extreme weather: fragility modeling, probabilistic impact assessment, and adaptation measures', *IEEE Trans. Power Syst.*, 2017, **32**, (5), pp. 3747–3757
[67] Dumas, M., Kc, B., Cunliff, C.I.: 'Extreme weather and climate vulnerabilities of the electric grid: a summary of environmental sensitivity quantification methods', 2019, ORNL/TM-2019/1252
[68] Espinoza, S., Poulos, A., Rudnick, H., *et al.*: 'Risk and resilience assessment with component criticality ranking of electric power systems subject to earthquakes', *IEEE Syst. J.*, 2020, **14**, (2), pp. 2837–2848
[69] Li, G., Huang, G., Bie, Z., *et al.*: 'Component importance assessment of power systems for improving resilience under wind storms', *J. Mod. Power Syst. Clean Energy*, 2019, **7**, pp. 676–687
[70] Rodriguez-Espindola, O., Albores, P., Brewster, C.: 'Disaster preparedness in humanitarian logistics a collaborative approach for resource management in floods', *Eur. J. Oper. Res.*, 2018, **264**, (3), pp. 978–993
[71] Arab, A., Khodaei, A., Khator, S.K., *et al.*: 'Stochastic pre-hurricane restoration planning for electric power systems infrastructure', *IEEE Trans. Smart Grid*, 2015, **6**, pp. 1046–1054
[72] Wang, B., Sarker, R., Mann, L., *et al.*: 'Resource planning and a depot location model for electric power restoration', *Eur. J. Oper. Res.*, 2004, **155**, (1), pp. 22–43
[73] Coffrin, C., Hentenryck, P.V., Bent, R.: 'Strategic stockpiling of power system supplies for disaster recovery'. Proc. IEEE Power Eng. Soc. General Meeting, San Diego, CA, USA, 2011, pp. 1–8
[74] Curcic, S., Ozveren, C.S., Crowe, L., *et al.*: 'Electric power distribution network restoration: a survey of papers and a review of the restoration problem', *Electr. Power Syst. Res.*, 1995, **35**, pp. 73–86
[75] Zidan, A., Khairalla, M., Abdrabou, A.: 'Fault detection, isolation, and service restoration in distribution systems: state-of-the-art and future trends', *IEEE Trans. Smart Grid*, 2017, **8**, (5), pp. 2170–2185
[76] Singh, S.P., Raju, G.S., Rao, G.K., *et al.*: 'A heuristic method for feeder reconfiguration and service restoration in distribution networks', *Int. J. Electr. Power Energy Syst.*, 2009, **31**, (8), pp. 309–314
[77] Manjunath, K., Mohan, M.R.: 'A new hybrid multi-objective quick service restoration technique for electric power distribution systems', *Int. J. Electr. Power Energy Syst.*, 2007, **29**, (1), pp. 51–64
[78] Jiang, Y., Jiang, J., Zhang, Y.: 'A novel fuzzy multiobjective model using adaptive genetic algorithm based on cloud theory for service restoration of shipboard power systems', *IEEE Trans. Power Syst.*, 2012, **27**, (2), pp. 612–620
[79] Khushalani, S., Solanki, J.M., Schulz, N.N.: 'Optimized restoration of unbalanced distribution systems', *IEEE Trans. Power Syst.*, 2007, **22**, (2), pp. 624–630
[80] Zidan, A., El-Saadany, E.F.: 'A cooperative multiagent framework for self-healing mechanisms in distribution systems', *IEEE Trans. Smart Grid*, 2012, **3**, (3), pp. 1525–1539
[81] Van Hentenryck, P., Coffrin, C., Bent, R.: 'Vehicle routing for the last mile of power system restoration'. Proc. 17th Power Syst. Computation Conf., Stockholm Sweden, 2011, pp. 1–8

[82] Arif, A., Ma, S., Wang, Z.: 'Optimization of transmission system repair and restoration with crew routing'. NAPS 2016 – 48th North American Power Symp., Proc., Denver, CO, USA, 2016, pp. 1–6
[83] Golla, B.: 'Routing line personnel for restoration of disrupted power distribution network', M.S. Thesis, University of North Carolina, Charlotte, 2017
[84] Hatziargyriou, N., Asano, H., Iravani, R., *et al.*: 'Microgrids', *IEEE Power Energy Mag.*, 2007, **5**, (4), pp. 78–94
[85] Dan, T., Smith, M.: 'The U.S. Department of energy's microgrid initiative', *Electr. J.*, 2012, **25**, (8), pp. 84–94
[86] CIGRE Working Group C.22: 'Microgrids 1, Engineering, Economics, and Experience', Paris, France, 2015
[87] Basak, P., Chowdhury, S., Dey, H., *et al.*: 'A literature review on integration of distributed energy resources in the perspective of control, protection and stability of microgrid', *Renew. Sustain. Energy Rev.*, 2012, **16**, (8), pp. 5545–5556
[88] Hatziargyriou, N.: '*Microgrids: architectures and control*' (John Wiley & Sons, The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, UK, 2013)
[89] Micallef, A., Apap, M., Spiteri-Staines, C., *et al.*: 'Single-phase microgrid with seamless transition capabilities between modes of operation', *IEEE Trans. Smart Grid*, 2015, **6**, (6), pp. 2736–2745
[90] Wang, J., Chang, C.P., Feng, X., *et al.*: 'Design of a generalized control algorithm for parallel inverters for smooth microgrid transition operation', *IEEE Trans. Ind. Electron.*, 2015, **62**, (8), pp. 4900–4914
[91] Palma-Behnke, R., Benavides, C., Lanas, F., *et al.*: 'A microgrid energy management system based on the rolling horizon strategy', *IEEE Trans. Smart Grid*, 2013, **4**, (2), pp. 996–1006
[92] Cardoso, G., Stadler, M., Siddiqui, A., *et al.*: 'Microgrid reliability modeling and battery scheduling using stochastic linear programming', *Electr. Power Syst. Res.*, 2013, **103**, pp. 61–69
[93] Su, W., Wang, J., Roh, J.: 'Stochastic energy scheduling in microgrids with intermittent renewable energy resources', *IEEE Trans. Smart Grid*, 2014, **5**, (4), pp. 1876–1883
[94] Madureira, A.G., Pecas Lopes, J.A.: 'Coordinated voltage support in distribution networks with distributed generation and microgrids', *IET Renew. Power Gener.*, 2009, **3**, (4), pp. 439–454
[95] Beer, S., Gomez, T., Dallinger, D., *et al.*: 'An economic analysis of used electric vehicle batteries integrated into commercial building microgrids', *IEEE Trans. Smart Grid*, 2012, **3**, (1), pp. 1517–1525
[96] Tsikalakis, A.G., Hatziargyriou, N.D.: 'Centralized control for optimizing microgrids operation', *IEEE Trans. Energy Convers.*, 2008, **23**, (1), pp. 241–248
[97] Bower, W., Ton, D., Guttromson, R., *et al.*: 'The Advanced Microgrid Integration and Interoperability', Sandia National Laboratory report: SAND2014–1535, 2014
[98] Rocabert, J., Luna, A., Blaabjerg, F., *et al.*: 'Control of power converters in AC microgrids', *IEEE Trans. Power Electron.*, 2012, **27**, (11), pp. 4734–4749
[99] Vinayagam, A., Alqumsan, A.A., Swarna, K., *et al.*: 'Intelligent control strategy in the islanded network of a solar PV microgrid', *Electr. Power Syst. Res.*, 2018, **155**, pp. 93–103
[100] Ioan, S., Catalin, P.I.: 'Microgrid control based on a grid-forming inverter operating as virtual synchronous generator with enhanced dynamic response capability', *Int. J. Electr. Power Energy Syst.*, 2017, **89**, pp. 94–105
[101] Canizares, C.A., Palma-Behnke, R.: 'Trends in microgrid control IEEE-PES task force on microgrid control', *IEEE Trans. Smart Grid*, 2014, **5**, (4), pp. 1905–1919
[102] Guerrero, J.M., Chandorkar, M., Lee, T., *et al.*: 'Advanced control architectures for intelligent microgrids – part I: decentralized and hierarchical control', *IEEE Trans. Ind. Electron.*, 2013, **60**, (4), pp. 1254–1262
[103] Lin, J., Wang, X., Wang, P., *et al.*: 'Two-stage method for optimal island partition of distribution system with distributed generations', *IET Gener. Transm. Distrib.*, 2012, **6**, (3), pp. 218–225
[104] Chen, C., Wang, J., Qiu, F., *et al.*: 'Resilient distribution system by microgrids formation after natural disasters', *IEEE Trans. Smart Grid*, 2016, **7**, (2), pp. 958–966
[105] Ding, T., Lin, Y., Bie, Z., *et al.*: 'A resilient microgrid formation strategy for load restoration considering master-slave distributed generators and topology reconfiguration', *Appl. Energy*, 2017, **199**, pp. 205–216
[106] Wang, Y., Chen, C., Wang, J., *et al.*: 'Research on resilience of power systems under natural disasters: a review', *IEEE Trans. Power Syst.*, 2016, **31**, (2), pp. 1604–1613
[107] Chen, C., Wang, J., Ton, D.: Modernizing distribution system restoration to achieve grid resiliency against extreme weather events: an integrated solution', *Proc. IEEE*, 2017, **105**, (7), pp. 1267–1288
[108] FEMA (Federal Emergency Management Agency): P-1019: 'Emergency power systems for critical facilities: a best practices approach to improving reliability', 2014, Available at: https://www.fema.gov/media-library/assets/documents/101996
[109] Faraji, J., Babaei, M., Bayati, N., *et al.*: 'A comparative study between traditional backup generator systems and renewable energy based microgrids for power resilience enhancement of a local clinic', *Electronics (Basel)*, 2019, **8**, p. 1485
[110] Marqusee, J., Jenket, D.: 'Reliability of emergency and standby diesel generators: impact on energy resiliency solutions', *Appl. Energy*, 2020, **268**, p. 114918
[111] Waseem, I., Pipattanasomporn, M., Rahman, S.: 'Reliability benefits of distributed generation as a backup source'. Proc. IEEE PES General Meeting, Calgary AB, 2009, pp. 1–8
[112] Nazemi, M., Moeini-Aghtaie, M., Fotuhi-Firuzabad, M., *et al.*: 'Energy storage planning for enhanced resilience of power distribution networks against earthquakes', *IEEE Trans. Sustain. Energy*, 2020, **11**, (2), pp. 795–806
[113] The DG for Resilience Planning Guide: Available at https://dg.resilienceguide.lbl.gov/
[114] Zhou, L., Fan, M., Zhang, Z.: 'A study on the optimal allocation of emergency power supplies in urban electric network'. CIRED 2009 – 20th Int. Conf. and Exhibition on Electricity Distribution - Part 1, Prague, Czech Republic, 2009, pp. 1–4
[115] Shang, J., Sheng, X., Zhang, J., *et al.*: 'The optimized allocation of mobile emergency generator based on the loads importance'. 2009 Asia-Pacific Power and Energy Engineering Conf., Wuhan, 2009, pp. 1–4
[116] Hussain, A., Bui, V., Kim, H.: 'A proactive and survivability-constrained operation strategy for enhancing resilience of microgrids using energy storage system', *IEEE Access*, 2018, **6**, pp. 75495–75507
[117] Amirioun, M.H., Aminifar, F., Shahidehpour, M.: 'Allocation of resources using a microgrid formation approach for resilient electric grids', *IEEE Trans. Power Syst.*, 2019, **34**, (3), pp. 2160–2168
[118] Teodorescu, R., Blaabjerg, F.: 'Flexible control of small wind turbines with grid failure detection operating in stand-alone and grid-connected mode', *IEEE Trans. Power Electron.*, 2004, **19**, (5), pp. 1323–1332
[119] Katiraei, F., Iravani, R., Hatziargyriou, N., *et al.*: 'Microgrids management', *IEEE Power Energy Mag.*, 2008, **6**, (3), pp. 54–65
[120] Zidan, A., El-Saadany, E.F.: 'Service restoration in balanced and unbalanced distribution systems with high DG penetration'. 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 2011, pp. 1–8
[121] Sharma, A., Srinivasan, D., Trivedi, A.: 'A decentralized multiagent system approach for service restoration using DG islanding', *IEEE Trans. Smart Grid*, 2015, **6**, (6), pp. 2784–2793
[122] Wang, Y., Xu, Y., He, J., *et al.*: 'Coordinating multiple sources for service restoration to enhance resilience of distribution systems', *IEEE Trans. Smart Grid*, 2019, **10**, (5), pp. 5781–5793
[123] Kim, J., Dvorkin, Y.: 'Enhancing distribution system resilience with mobile energy storage and microgrids', *IEEE Trans. Smart Grid*, 2019, **10**, (5), pp. 4996–5006
[124] Yao, S., Wang, P., Zhao, T.: 'Transportable energy storage for more resilient distribution systems with multiple microgrids', *IEEE Trans. Smart Grid*, 2019, **10**, (3), pp. 3331–3341
[125] Lei, S., Chen, C., Zhou, H., *et al.*: 'Routing and scheduling of mobile power sources for distribution system resilience enhancement', *IEEE Trans. Smart Grid*, 2019, **10**, (5), pp. 5650–5662
[126] Mishra, S., Anderson, K., Miller, B., *et al.*: 'Microgrid resilience: a holistic approach for assessing threats, identifying vulnerabilities, and designing corresponding mitigation strategies', *Appl. Energy*, 2020, **264**, p. 114726
[127] Yamangil, E., Bent, R., Backhaus, S.: 'Resilient upgrade of electrical distribution grids'. Proc. 29th AAAI Conf. on Artificial Intelligence, Austin, TX, USA, 2015, pp. 1233–1240
[128] Wang, Z., Chen, B., Wang, J., *et al.*: 'Robust optimization based optimal DG placement in microgrids', *IEEE Trans. Smart Grid*, 2014, **5**, (5), pp. 2173–2182
[129] Sedzro, K., Lamadrid, A.J., Zuluaga, L.: 'Allocation of resources using a microgrid formation approach for resilient electric grids', *IEEE Trans. Power Syst.*, 2018, **33**, (3), pp. 2633–2643
[130] Wu, X., Wang, Z., Ding, T., *et al.*: 'Microgrid planning considering the resilience against contingencies', *IET Gener. Transm. Distrib.*, 2019, **13**, (16), pp. 3534–3548
[131] Xu, Y., Liu, C., Schneider, K.P., *et al.*: 'Toward a resilient distribution system'. Proc. IEEE PES General Meeting, Denver CO, 2015, pp. 1–5
[132] Davis, G., Snyder, A.F., Mader, J.: 'The future of distribution system resiliency'. Proc. 2014 Clemson Univ. Power Syst. Conf., Clemson SC, 2014, pp. 1–8
[133] Liu, G., Starke, M., Xiao, B., *et al.*: 'Robust optimization based microgrid scheduling with islanding constraints', *IET Gener. Transm. Distrib.*, 2017, **11**, pp. 1820–1828
[134] Liu, G., Starke, M., Xiao, B., *et al.*: 'Microgrid optimal scheduling with chance-constrained islanding capability', *Electr. Power Syst. Res.*, 2017, **145**, pp. 197–206
[135] Khodaei, A.: 'Microgrid optimal scheduling with multi-period islanding constraints', *IEEE Trans. Power Syst.*, 2014, **29**, (3), pp. 1383–1392
[136] Khodaei, A.: 'Resiliency-oriented microgrid optimal scheduling', *IEEE Trans. Smart Grid*, 2014, **5**, (4), pp. 1584–1591
[137] Gholami, A., Shekari, T., Aminifar, F., *et al.*: 'Microgrid scheduling with uncertainty: the quest for resilience', *IEEE Trans. Smart Grid*, 2016, **7**, (6), pp. 2849–2858
[138] Liu, G., Xiao, B., Starke, M., *et al.*: 'A robust load shedding strategy for microgrid islanding transition'. Proc. IEEE Power Engineering Society Transmission and Distribution Conf., Dallas, TX, USA, 2016, pp. 1–5
[139] Pan, Y., Chen, L., Lu, X., *et al.*: 'Stability region of droop-controlled distributed generation in autonomous microgrids', *IEEE Trans. Smart Grid*, 2019, **10**, (2), pp. 2288–2300
[140] Amirioun, M.H., Aminifar, F., Lesani, H.: 'Resilience-oriented proactive management of microgrids against windstorms', *IEEE Trans. Power Syst.*, 2018, **33**, (4), pp. 4275–4284
[141] Gholami, A., Sun, A.: 'Towards resilient operation of multimicrogrids: an MISOCP-based frequency-constrained approach', *IEEE Trans. Control Netw. Syst.*, 2019, **6**, (3), pp. 925–936
[142] Shi, Q., Li, F., Cui, H.: 'Analytical method to aggregate multi-machine SFR model with applications in power system dynamic studies', *IEEE Trans. Power Syst.*, 2018, **33**, (6), pp. 6355–6367
[143] Say, B., Wu, G., Zhou, Y.Q., *et al.*: 'Nonlinear hybrid planning with deep net learned transition models and mixed-integer linear programming'. IJCAI Int. Joint Conf. Artificial Intelligence, Melbourne, Australia, 2017, pp. 750–756
[144] Lopes, J.A.P., Moreira, C.L., Madureira, A.G.: 'Defining control strategies for microgrids islanded operation', *IEEE Trans. Power Syst.*, 2006, **21**, (2), pp. 916–924

[145] Che, L., Shahidehpour, M.: 'DC microgrids: economic operation and enhancement of resilience by hierarchical control', *IEEE Trans. Smart Grid*, 2014, **5**, (5), pp. 2517–2526
[146] Gao, H., Chen, Y., Xu, Y.*, et al.*: 'Dynamic load shedding for an islanded microgrid with limited generation resources', *IET Gener. Transm. Distrib.*, 2016, **10**, pp. 2953–2961
[147] Hong, Y., Hsiao, M., Chang, Y.*, et al.*: 'Multiscenario underfrequency load shedding in a microgrid consisting of intermittent renewables', *IEEE Trans. Power Deliv.*, 2006, **28**, (3), pp. 1610–1617
[148] Pashajavid, E., Shahnia, F., Ghosh, A.: 'Development of a self-healing strategy to enhance the overloading resilience of islanded microgrids', *IEEE Trans. Smart Grid*, 2017, **8**, (2), pp. 868–880
[149] Wang, M., Gooi, H.B.: 'Spinning reserve estimation in microgrids', *IEEE Trans. Power Syst.*, 2011, **26**, (3), pp. 1164–1174
[150] Moreira, C., Resende, F., Lopes, J.: 'Using low voltage microgrids for service restoration', *IEEE Trans. Power Syst.*, 2007, **22**, (1), pp. 395–403
[151] Gao, H., Chen, Y., Xu, Y.*, et al.*: 'Resilience-oriented critical load restoration using microgrids in distribution systems', *IEEE Trans. Smart Grid*, 2016, **7**, (6), pp. 2837–2848
[152] Xu, Y., Liu, C., Schneider, K.*, et al.*: 'Microgrids for service restoration to critical load in a resilient distribution system', *IEEE Trans. Smart Grid*, 2018, **9**, (1), pp. 426–437
[153] Chen, B., Chen, C., Wang, J.*, et al.*: 'Multi-time step service restoration for advanced distribution systems and microgrids', *IEEE Trans. Smart Grid*, 2018, **9**, (6), pp. 6793–6805
[154] Chen, B., Chen, C., Wang, J.*, et al.*: 'Sequential service restoration for unbalanced distribution systems and microgrids', *IEEE Trans. Power Syst.*, 2018, **33**, (2), pp. 1507–1520
[155] Arif, A., Wang, Z., Wang, J.*, et al.*: 'Power distribution system outage management with co-optimization of repairs, reconfiguration, and DG dispatch', *IEEE Trans. Smart Grid*, 2018, **9**, (5), pp. 4109–4118
[156] Ding, T., Lin, Y., Li, G.*, et al.*: 'A new model for resilient distribution systems by microgrids formation', *IEEE Trans. Power Syst.*, 2017, **32**, (5), pp. 4145–4147
[157] Wang, Z., Wang, J.: 'Self-healing resilient distribution systems based on sectionalization into microgrids', *IEEE Trans. Power Syst.*, 2015, **30**, (6), pp. 3139–3149
[158] Wang, Z., Chen, B., Wang, J.*, et al.*: 'Decentralized energy management system for networked microgrids in grid-connected and islanded modes', *IEEE Trans. Smart Grid*, 2015, **7**, (2), pp. 1097–1105
[159] Arif, A., Wang, Z.: 'Networked microgrids for service restoration in resilient distribution systems', *IET Gener. Transm. Distrib.*, 2017, **11**, (14), pp. 3612–3619
[160] Wang, Z., Chen, B., Wang, J.*, et al.*: 'Networked microgrids for self-healing power systems', *IEEE Trans. Smart Grid*, 2016, **7**, (1), pp. 310–319
[161] Farzin, H., Fotuhi-Firuzabad, M., Moeini-Aghtaie, M.: 'Enhancing power system resilience through hierarchical outage management in multi-microgrids', *IEEE Trans. Smart Grid*, 2016, **7**, (6), pp. 2869–2879
[162] Castillo, A.: 'Microgrid provision of blackstart in disaster recovery for power system restoration'. Proc. 2013 IEEE Int. Conf. Smart Grid Communication, Vancouver, BC, Canada, 2013, pp. 534–539
[163] Schneider, K.P., Tuffner, F.K., Elizondo, M.A.*, et al.*: 'Evaluating the feasibility to use microgrids as a resiliency resource', *IEEE Trans. Smart Grid*, 2017, **8**, (2), pp. 687–696
[164] Zhao, Y., Lin, Z., Ding, Y.*, et al.*: 'A model predictive control based generator start-up optimization strategy for restoration with microgrids as black-start resources', *IEEE Trans. Power Syst.*, 2018, **33**, (6), pp. 7189–7203