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Microgrids as a resilience resource and strategies used by microgrids for enhancing resilience

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HIGHLIGHTS

- Resilience of power systems and extreme weather events is analyzed.
- Formation of microgrids for resilience enhancement is reviewed.
- Strategies used by microgrids for enhancing resilience are reviewed.
- Future directions for resilience-oriented operation methods are presented.

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ABSTRACT

Microgrids are considered as a potential solution to deal with major power disruption events due to their ability of islanding and potential to sustain the penetration of renewables. In order to elaborate the role of microgrids in enhancing the resilience of power systems, a three-step analysis is carried out in this paper. In the first step, the general backgrounds of resilience in power systems are presented, which comprise of disaster modeling, resilience analysis methods, and resilience enhancement efforts by different regions. In the second step, the use of microgrids as a resilience resource is analyzed, where formation of microgrids, networked microgrids, and dynamic microgrids along with resiliency of multi-energy networks are explored. In the third step, the strategies utilized by microgrids for enhancing their resilience during major outage events are analyzed. These strategies include proactive scheduling, outage management, feasible islanding, and advanced operation strategies for reducing the impact of major disruptions. The classification of these operation strategies is based on the event occurrence and clearance times. In addition, the resilience strategies used by different types of microgrids, types of energy management systems, communication resilience, and resilience of individual components in microgrids are also analyzed. Finally, research gaps in the existing literature and future directions for improving the available resilience-oriented operation methods for enhancing the resilience of microgrids are presented.

1. Introduction

Resilience enhancement of power grids against natural disasters has become a major consideration for power and energy sector researchers and engineers in recent years. Due to lesser incidences of natural disasters, these events were initially known as low-probability high-impact events. However, the frequency of these events has increased in the last few decades due to climate change [1]. Among various other major events, the intensity and severity of weather-related events have significantly increased in the last decades [2]. Seven of the ten major storms that occurred during the last four decades have occurred in the last 10 years and each event caused damages of over 1-billion dollars [3]. In 2017 only, eight major weather-related events have struck the world, especially the US [4–11]. Five of these eight events have disrupted power to over a million consumers and the least number of consumers affected during any single event were around 0.3million.

The existing electrical power systems can assure service reliability during normal conditions and abnormal but foreseeable and low impact contingencies. However, the continuity of service during unexpected and high impact events is still a challenge [12]. Therefore, existing power systems are known to be reliable but not resilient. The resiliency of a system is defined as its ability to return to the equilibrium (stable operation point) after a major disruption event [13]. Due to the absence of a universally accepted definition of resilience in power systems, the authors in [14] have analyzed various aspects of system resilience and defined the power system resilience. In [14], the cyber-physical

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resilience of power systems is defined as the ability of the power system to sustain low-probability high-impact events by feeding at least the most-critical loads.

In order to enhance the resiliency of power systems against these major events, various studies and surveys are conducted across the world, which include disaster modeling [1,15–18], resilience analysis [16,19–26], generalized resilience enhancement methods [27–30], and long/short term resilience plans [27,31–34]. Some localities are more prone to particular types of natural disasters. Therefore, various regions have carried out resilience enhancement measures considering their local environments [35–39] and the impact of past events is analyzed [40–45]. Various solutions were proposed by these studies to prepare and adopt the power systems to these diverse natural disasters. Among the proposed solutions in these studies, some of the solutions are common in most of the studies. These common solutions include integration of distributed energy sources, microgrid formulation, and line hardening [17,28–30,33,46]. Among the most common solutions, mentioned above, use of microgrids for resiliency enhancement has gained popularity. This is due to the ability of microgrids to sustain the penetration of renewables and ability of islanding, i.e. ability to feed critical loads during system contingencies.

Microgrids are generally used as a resilience resource to enhance the resilience of power systems during major events. During major disruption events, the on-outage area is isolated from the main grid and it is divided into self-sufficient microgrids using tie switches. In some cases, microgrids are coupled to support the critical loads of other microgrids of the network having insufficient supply [47]. In this way, microgrids can either be used as a local resource or as a community resource to enhance the resiliency of the power systems. In addition, microgrids can be used as a black-start resource to start the main generators, which were disrupted due to natural disasters [48]. Therefore, in contrast to conventional power systems, the self-healing process can be simultaneously triggered at distribution and generation levels to enhance the resilience of power systems [49]. The resilience of power systems can be increased either by transforming existing power systems into microgrids [50–53], by forming dynamic microgrids [54–59], or by forming networked microgrids [60–66]. In addition to power only microgrids, resilience analysis and resilience enhancement strategies for multi-energy microgrids and energy hubs are also available in the literature [67–73].

In addition to using microgrids as resilience resource, strategies used by microgrids for enhancing their resilience during major outage events is another research area, which has attracted the attention of researchers. Microgrids need to schedule their resources to assure the feasible islanding during any disruption event. In addition, microgrids need to assure the survivability of local/community critical loads during the emergency period. In order to enhance the resilience of microgrids, recently various studies are conducted. These studies include proactive scheduling [17,33,65,74–77], outage management [31,32,63,78–85], and advanced operation strategies [86–95]. In proactive operation schemes, various scheduling approaches are used and the commitment statuses of local resources are revised to assure the feasible islanding during any potential event. During outage management, the priority of loads is defined and survivability of critical loads is enhanced via local resources during the emergency period. Finally, in the case of advanced operation strategies, multi-agent systems or other artificial intelligence techniques are utilized. Different techniques for various microgrid types [54–56,60,65,78,79,96–101] and different architecture-based resilience enhancement strategies [55–57,65,74,101,102] are also available in the literature. The resilience of communication system for microgrids [103–108], analysis specific to particular events [75,109–112], and resilience of individual components of the power systems [113–116] are also available.

In order to emphasize the importance of microgrids in enhancing the resilience of power systems, a literature review is conducted in this study. Initially, the concept of resilience in power systems, the occurrence of extreme weather events, and general strategies for enhancing the resilience of the power system are reviewed. Then, the role of microgrids for enhancing the resilience of power systems and strategies used by microgrids for enhancing their resilience are analyzed separately in two parts. In the first part, the formation of microgrids, the formation of networked microgrids, the resilience of multi-energy power systems, and the formation of dynamic microgrids are analyzed. In the second part, strategies used by microgrids for enhancing their resilience are explored. In this part, proactive scheduling, outage management, networking of microgrids, and advanced operation strategies for reducing restoration time during the islanded operation are analyzed. The resilience operation strategies specific to microgrid type and different microgrid architectures and their impact on microgrid resilience are also analyzed. Finally, the resilience of communication systems, resilience measures for specific events, and the resilience of individual components in microgrids are analyzed. Throughout the paper, major event, extreme event, major disruption event, and major outages are interchangeably used. All these terms refer to natural disasters, extreme weather events, and other man-made large-scale events, i.e. events specific to system resilience. An overview of section-wise

Table 1
Overview of section-wise research areas and corresponding references.

Section	Main research area	Sub-section	Sub-area	References
2	Resilience of Power Systems	2.1	Reliability vs Resiliency	[27,118]
		2.2	Disaster Modeling	[1,15–18]
		2.3	Resilience Analysis	[16,19–26]
		2.4	Resilience Enhancement Methods	[27–34]
		2.5	Extreme Weather Events	[4–11]
		2.6	Resilience Enhancement Efforts by Different Regions	[35–45]
3	Microgrids as a Resilience Resource: Microgrid Formation	3.1	Transformation of Conventional Power Networks into Microgrids	[50–53]
		3.2	Dynamic Microgrid Formation	[54–59]
		3.3	Networked Microgrid Formation	[60–66]
		3.4	Multi-Energy Microgrids and Energy Hubs	[67–73]
4	Strategies Used by Microgrids for Enhancing Resilience	4.1	Proactive Scheduling	[17,33,65,74–77]
		4.2	Outage Management	[31,32,63,78–85]
		4.3	Advanced Operation Strategies	[86–95]
		4.4	Resilience Enhancement Methods for AC, DC, and Hybrid Microgrids	[54–56,60,65,78,79,96–101]
		4.5	Centralized, Decentralized, and Hierarchical Methods	[55–57,65,74,101,102]
5	Communication, Event-Specific, and Component Resilience	5.1	Communication Resilience	[103–108]
		5.2	Event-Specific Resilience	[75,109–112]
		5.3	Resilience of Power Components	[113–116]

research areas introduced in the introduction section is given in Table 1.

The remainder of the paper is organized as follows. The introduction section is followed by backgrounds of power system resilience analysis, Section 2. In Section 3, the usage of microgrids as a resilience resource, i.e. microgrid formation is presented. The strategies used by microgrids for enhancing their resilience are analyzed in Section 4. Section 5 covers the resilience of communication network, event-specific analysis, and microgrid component resilience analysis. The research gaps and future research directions are presented in Section 6, which is followed by the conclusions section, Section 7.

2. Resilience of power systems

This section gives an overview of the resilience concept in power systems and introduces different resilience analysis techniques and types of resilience enhancement methods available in the literature. Firstly, an overview of the resilience concept is presented and it is compared and contrasted with the commonly confused term *reliability* in the power systems. Secondly, disaster modeling, resilience analysis methods, and resilience quantification techniques available in the literature are summarized. Thirdly, the desired performance of a resilient power system and types of resilience enhancement methods available in the literature are presented in a broader spectrum. Finally, an overview of the extreme weather events, the major cause of power outages, along with a summary of major outages of 2017 are presented.

The electric power system has undergone many changes from the humble beginnings in the 1880s [117]. The current power systems are known to be reliable, i.e. they can provide reliable power to the customers during normal and abnormal but foreseeable contingencies. The modern power systems still lack the resiliency features, i.e. they are unable to sustain major natural disasters like storms, floods, hurricanes, earthquakes, etc. Therefore, several studies are underway to enhance the resilience of power systems. However, due to the interdisciplinary nature and complexity of the problem, studies are conducted sparsely on different domains [118].

2.1. Reliability vs resiliency

In power systems, reliability is often considered as synonymous to resiliency but it has some major differences with the resiliency as highlighted in Fig. 1. The ability of a power system to sustain the occurrence of typical power system outages is defined as the reliability. In case of typical power system outages, usually, one or two random faults cause outages [118]. A load restoration method is required to energize the on-outage areas by allocating loads to active generators. Several load restoration techniques for typical power system outages are available in the literature [118].

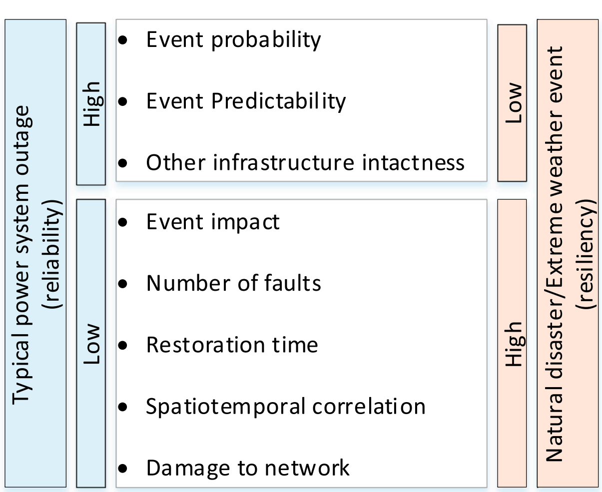

Fig. 1. Comparison of reliability and resiliency [118].

In case of extreme events (natural disasters), multiple and cascaded outages occur and also the transmission and/or distribution networks may be damaged. In addition, natural disasters may destroy other networks also, which may adversely influence the power network, i.e. communication and transportation networks. This makes the restoration process during natural disasters more challenging. The conventional power system restoration techniques, which are developed for typical power system outages, may not be effective [27]. Therefore, resiliency evaluation methods and resiliency enhancement techniques available in the literature are summarized in the following sections.

2.2. Disaster modeling

Disaster modeling is foundation for resilience analysis and various studies have been conducted to model the desired performance of the system during major outages. In order to visualize the behavior of the power systems during a catastrophic event, a resilience trapezoid is introduced by [16]. Different operation goals for various phases of the event can be visualized from the proposed trapezoid. In [17], intially a resilience triangle is proposed to visualize the power system performance during events, which was later updated to a esilience trapezoid, as shown in Fig. 2. It can be observed from Fig. 2 that a resilient power system tends to decrease the withstanding, adaptation, and recovery times in comparison to a conventional power system without resiliency features. The resilience of power lines and power towers are analyzed for different extreme weather events using fragility curves by [1]. The fragility curves can be formulated by using the data on a number of faults against the severity of a particular parameter. Fragility curves of individual components and the entire power network are built for mapping the impact of wind on their failure probabilities by [18]. The risks of power outages from natural disasters are modeled in [15], where Bayesian approach is suggested to estimate the posterior curves based on the prior curves and the wind speed information.

2.3. Resilience analysis

In this section, various resilience analysis techniques, resilience quantification methods, and metrics available in the literature are summarized. In [18,119] probabilistic resilience analysis methods with a focus on weather-related events are proposed. Artificial neural networks are trained by [119] for emulating the total load shedding given

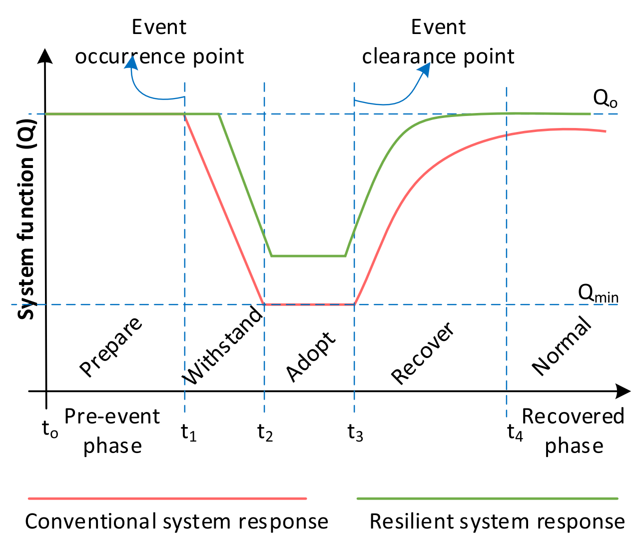

Fig. 2. Resilient vs conventional system performance during events [29].

the line failure probability and the load profiles. Various resilience metrics are proposed by [16,19,20] for assessing the resilience of power systems. Resilience metrics for withstanding capability and recovery speed of power systems are proposed by [19]. The authors of [20] have developed various resilience metrics for critical infrastructure by considering the future performance of the system under a given threat.

The performance of the proposed resilience metrics mentioned in the previous paragraph is assessed for various possible solutions by [21–23]. In [21], the resiliency of a dynamic power systems is analyzed for different technologies, i.e. energy storage elements, demand-side management, and distributed generations. Resilience metrics are used to strengthen the collaboration between disaster management teams and critical infrastructure providers for resiliency enhancement of power system by [22]. The vulnerability of low-income houses in developing countries are reviewed by [23] using five sustainability assessment tools. Four major limitations have been identified based on the analysis, details can be seen in [23].

The multi-phase resilience of power systems is analyzed in [24] by considering robust, redundant, and responsive cases considering pre and post-event analysis. Designing of resilient control architecture is considered in [25] for various possible events in power systems and cost-benefit analysis is carried out for various designs and policies. The summary of major power outage events and their causes can be seen in Fig. 3 [26].

2.4. Resilience enhancement methods

Resilience enhancement methods of power systems can be divided into three major phases based on the event occurrence and clearance times as shown in Fig. 4. In the pre-event phase, the outage of power equipment is estimated and power systems are prepared for any possible event through hardening, vegetation, etc. [118]. During, the on-event phase, network is reconfigured, backup generations or energy storage systems are operated, available resources are re-scheduled, and load-shedding is carried out to absorb the effects of the event [28]. Finally, in the post-event phase, the network is derived back to the normal or near to normal condition by reconfiguring the network and re-energizing the power network (generation black-start) [29]. Several methods for enhancing the resiliency during emergency and recovery phases are proposed by [30].

The power system resilience enhancement plans can be broadly divided into long-term and short-term plans as shown in Fig. 5. The long-term solutions include transmission and/or distribution system upgrading, sensor deployment, network redundancy, and relocation of facilities [31,32,46]. Short-term plans include usage of demand response, microgrids, distributed energy resources, advanced visualization, and forecasting techniques, and decentralized control methods [27,29,33,118,34].

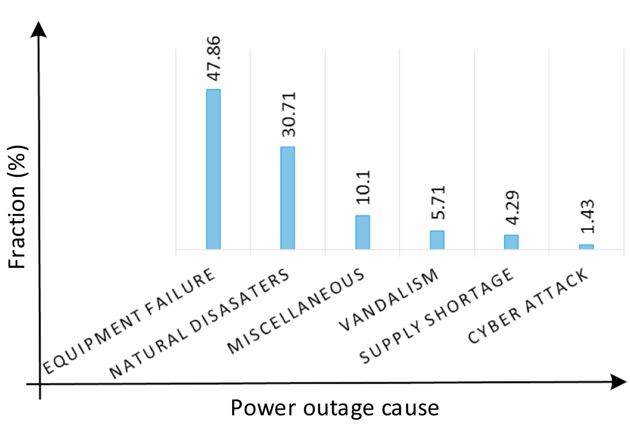

Fig. 3. Major power outage events and causes [26].

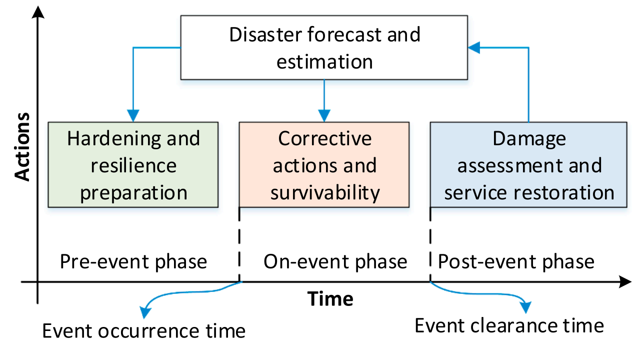

Fig. 4. Resilience enhancement in different phases [118].

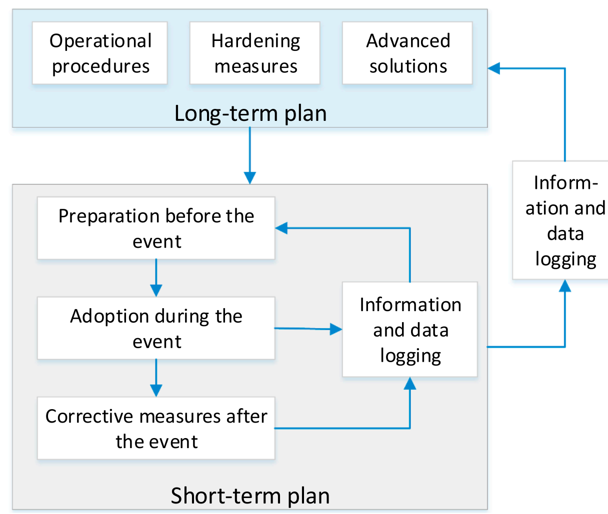

Fig. 5. Long and short-term resilience enhancement plans [27].

2.5. Extreme weather events

Among various other major events, extreme weather events have caused major outages in recent years. The intensity and frequency of these events are predicted to increase in the near future due to climate change [5]. Therefore, in this section, an overview of different extreme weather events is presented and the major outage events of the year 2017 are presented to emphasize the ratio of extreme weather events.

Weather-related events may occur due to several reasons, i.e. high/low temperatures, bad weather, change in wind speed and direction, etc. A list of possible weather-related events is shown in Fig. 6. Nine major outages have occurred in the year 2017 only, as shown in

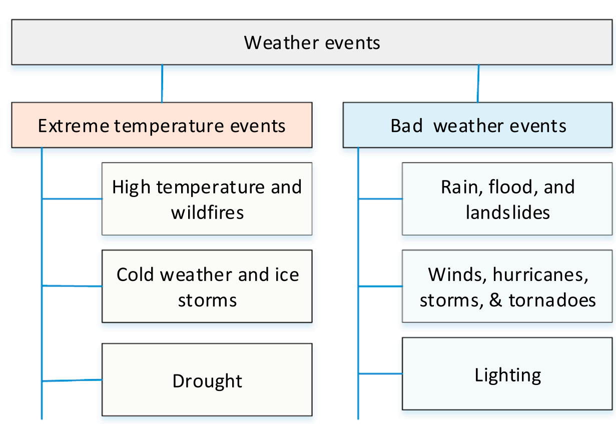

Fig. 6. Categories and causes of weather events [26].

Table 2
Major outages and their causes in 2017.

Month	Region	Affected people	Cause
Feb. 25 [4]	USA	258k	Severe wind
Mar. 1, 8 [5]		10 million	Typhoon
Jul. 1 [6]		Millions	Transmission line outage
Aug. 15 [7]	Taiwan		Power plant malfunction
Aug. 26 [8]	USA	910k	Bad weather
Sep. 10 [9]		7.6 million	Hurricane Irma
Sep. 20 [10]		15 million	Hurricane Maria
Oct. 30 [11]	US & Canada	Millions	Strom
Dec.7–10 [8]	USA	900k	Winter storm

Table 2. Seven among these nine outages were due to weather-related events and most of them have arisen in the USA.

2.6. Resilience enhancement efforts by different regions

Some of the localities are more prone to a certain type of natural disasters than others due to their geographical location. Therefore, several countries and regions have carried out various resilience enhancement measures subjected to particular disasters and resilience enhancement strategies are proposed. A summary of the efforts from different regions is presented in Table 3. The resilience of England's distribution network against floods is analyzed in [35] and the lessons learn from the past events are used to incorporate resiliency into the future planning. Similarly, the impact of climate change, specifically flooding risks in Bangladesh are analyzed in [38] and future planning practices are directed.

A report summary for enhancing the resilience of critical equipment of Rhode Island is drafted by Catlec Energy [39] and the full report can be found in [40]. Similarly, a report summary along with the full report for enhancing the resilience of critical infrastructure in the New York state can be found in [41] and [42], respectively. A report for enhancing the resiliency of Maryland by adopting microgrids has been presented by [43] and a report for integrating distributed generators in California distribution network by [44]. It has been concluded in this report that microgrid adaptation can help in sustaining the impacts of major natural disasters in the future.

In [45], after analyzing the current modeling, reliability, and restoration methods, several recommendations are made for the UK's power system. These recommendations include near-term, mid-term, and long-term objectives and plans for future power systems to deal with natural disasters. The resilience of the US power system is analyzed by [36,37] and future directions are suggested. Both of the studies have concluded that penetration of microgrids can assure survivability of critical loads during disasters by feeding critical loads. By reconfiguring the existing networks, microgrids can also be used to serve critical loads beyond their boundaries.

The role of microgrids for enhancing the resilience of specific localities and lessons learned from the previous events are summarized in [120–123]. In [120], the advanced design and control approaches used in the implementation of a resilient and sustainable microgrid in Bronzeville, Chicago are analyzed. The near future sustainable energy generation goals of the EU are analyzed in [121] and various solutions are proposed for the adoption of the renewables and to enhance the resilient performance of the grids. The lessons learned from the major earthquake of Japan in 2011 are summarized in [122] and faring of two microgrids during that event is analyzed. In addition, the ongoing research in Japan on the resilience-oriented deployment of microgrids is also reviewed. The role of microgrids for sustaining railway networks in emergency situations is analyzed by [123].

3. Microgrids as a resilience resource: microgrid formation

Microgrids can provide both financial and socio-economic benefits for the integration and adaptation of locally produced renewable energy [124]. The microgrid concept is now moving towards the development phase and several test sites and real-world microgrids are being developed across the globe [125]. These microgrids can be divided into basic autonomous, fully autonomous, and networked microgrids depending on their capability to feed all the local loads during the entire day [126]. The integration of energy storage at microgrids level or community level could have different benefits as demonstrated in [127].

The interest in microgrids is even more increasing, due to an increase in the number of major outage events and the damage caused by these events to power and other related networks [128]. These major events are either natural disasters or human-triggered events. Among various other solutions, microgrids have emerged as a potential solution for sustaining or softening the impacts of such major events. Microgrids can enhance the resilience of power systems due to their ability of islanding and potential of sustaining the penetration of renewables. Islanding can isolate the healthy parts of the network from the faulty parts. Renewables can fulfill the local critical loads during the emergency period in the absence of the connection with the utility grid. Although there are several types of microgrids and deployment objectives of each category could be different. One of the complementary benefits of all types of microgrids is their islanded operation, i.e. ability to survive their critical loads during system contingencies. Energy reliability to consumers during disruption events has been a major consideration in recent years and various researches are available in the literature [76,129,130]. Optimal capacity of hybrid renewables for energy reliability of cities has been determined by [129]and the integration of renewable energy sources in microgrids is analyzed by [130]. A two-step reliability-oriented method for reserve capacity and reliable power supply to consumers is studied in [131]. It can be concluded that a resilient power grid can be realized by integrating various microgrids [49].

The operation of microgrids for enhancing the resilience of power can be divided into three major types (Fig. 7), i.e. as a local resource, as

Table 3
Summary of efforts from different regions and countries for resilience enhancement.

Country/Region	Considered factors	Reference(s)
England, UK	Resilience against floods	[35]
Bangladesh	Food risks and potential measures	[38]
Rhode Island, USA	Enhancing the resilience of critical equipment	[39,40]
New York, USA		[41,42]
Maryland, USA	Adoption of microgrids for resilience enhancement	[43]
California, USA	Integration of distributed generations for resilience enhancement	[44]
USA	Analysis of power system vulnerability against natural disasters and other major events	[36,37]
UK		[45]
Bronzeville, USA	Advanced design and control approaches for resilience	[120]
EU	Near future sustainable energy goals and resilience of power systems	[121]
Japan	Lessons learned from past events and on-going resilience measures	[122]

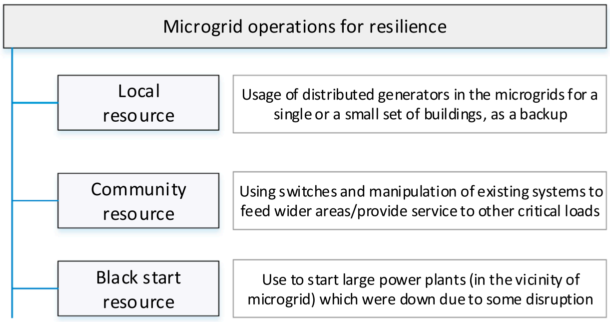

Fig. 7. Functions of microgrids as a resilience resource [48].

a community resource, and as a black start resource. In case of local resource, distributed generators are used as a backup resource for a single building or a set of a small number of buildings [48]. However, the network can be reconfigured to supply the power of one microgrid to feed the critical loads of another microgrid, i.e. microgrids as a community resource. Finally, microgrids can assist the starting of large generators, which have turned off due to a major event, i.e. microgrids as a black start resource. Microgrids not only increase the resilience of power systems but also increase the resilience of cities/districts by surviving critical infrastructures. The integration of renewable hybrid power systems in a residential district and analysis of the reliability of renewables and water harvester compared to electricity and water loads is carried out in [76].

During major disruption events, the objective is to restore the service to loads immediately. Conventionally, the restoration is carried out in a top-down way, i.e. generation black start followed by transmission network restoration, and then distribution network restoration. The loads can only be served after distribution network restoration. In this way, the outage duration of critical loads is elongated. If a microgrid is damaged during an outage event, the microgrid performs local self-healing immediately to survive maximum possible load. Simultaneously, the restoration process will also be commenced from the transmission side and progress toward the distribution grid. In this way, the whole restoration procedure would be performed parallel, a downward process from the transmission grid, together with an upward process from the distribution level [49]. In addition, microgrids in the vicinity of generation plants can assist the black-start of the conventional generators. A comparison of conventional and microgrid-based restoration processes is shown in Fig. 8.

3.1. Transformation of conventional power networks into microgrids

In this section, transformation of existing conventional power systems into microgrids is analyzed. This section falls under the long-term resilience enhancement category. In long-term resilience enhancement case, additional switches, distributed generators, and other physical devices are deployed to enhance the system resiliency. In order to transform a conventional distribution network into microgrids during disasters, optimal siting of switches is required. The authors of [50] have developed an algorithm for optimal allocation of tie switches considering investment costs and loss of load during disruptions due to the absence of switches. Similarly, a reconfigurable power system is suggested by [51] by coordinating local and system level resources for the resilience of power systems. More intelligence is added to the power electronic devices and a collaboration algorithm is devised for neighboring devices to handle possible faulty equipment for system reconfiguration. In [52], a resilient microgrid is formed in the first step. The obtained results are extended to apply for a conventional power distribution network in the later step. Decomposition of distribution networks into power independent microgrids is suggested by [53], as shown in Fig. 9. Distributed generators are optimally sized and deployed at optimal positions to reduce the power loss in the system while maximizing the sustainability of the system via locally distributed generators. During major disruption events, it may not be possible to survive all the loads of the networks. Therefore, load priorities are defined to ensure the service reliability to at least the most critical loads.

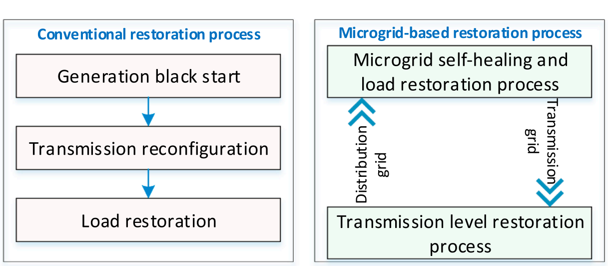

Fig. 8. Conventional vs microgrid-based restoration process [49].

3.2. Dynamic microgrid formation

Dynamic microgrid formulation followed by a catastrophic event can potentially enhance the resilience of the on-outage area by ensuring the self-sufficiency of the local loads. In this section, reconfiguration of existing microgrids during major outages is analyzed to enhance the resilience of microgrids. This section falls under the short-term resilience enhancement category. In short term resilience enhancement case, software algorithms are utilized to enhance the system resiliency by controlling the switches (deployed in long-term resiliency enhancement phase) and changing the configuration of the network. In A real-time re-configuration scheme for double busbar DC microgrids is developed by [54]. The objective is to rebuild resilient microgrids in real-time by distributing the load between the two buses to maintain self-sustainability of each bus. The operation modes of microgrids are divided into normal and self-healing modes by [55] and different operation schemes are devised for each mode. In normal mode, the objective of the microgrid is to minimize the operation cost of the microgrid. However, in the self-healing mode, the on-outage area is optimally divided into self-sufficient microgrids for the autonomous supply of power to the customers. A resilience enhancement strategy for reducing restoration time after the occurrence of an event is proposed by [56]. Self-organizing of microgrids is suggested by [56], where each microgrid has the choice to connect to the cluster. Each microgrid makes the decision after evaluating its local resources and load amount. In the second step, the microgrids of the cluster negotiate to decide optimal power sharing among the microgrids. A graph theory-based approach is used in [59] for optimal formation of microgrids by considering two layers. In the lower layer, optimal microgrids are formed and in the upper layer, optimal energy management of newly formed microgrids is determined. A master-slave approach is proposed in [132] for optimal formation of microgrids after a major event. In each island, one master DG is selected to guarantee the self-adequacy of the system. The operation of automatic switches is considered in [57] to form local microgrids by using the information of energized distributed generators after a major event. In addition, an algorithm for discovering global information of the network by using only local information is also proposed. The resilience of both communication and power networks during catastrophic events is considered by [57]. A model for reducing the computation burden on the energy management system of microgrids during disruptive events is formulated by [58], which can be utilized to reformulate the microgrid formation problem.

3.3. Networked microgrid formation

Geographically closely located microgrids can be networked to support each other during major disruption events as shown in Fig. 10a

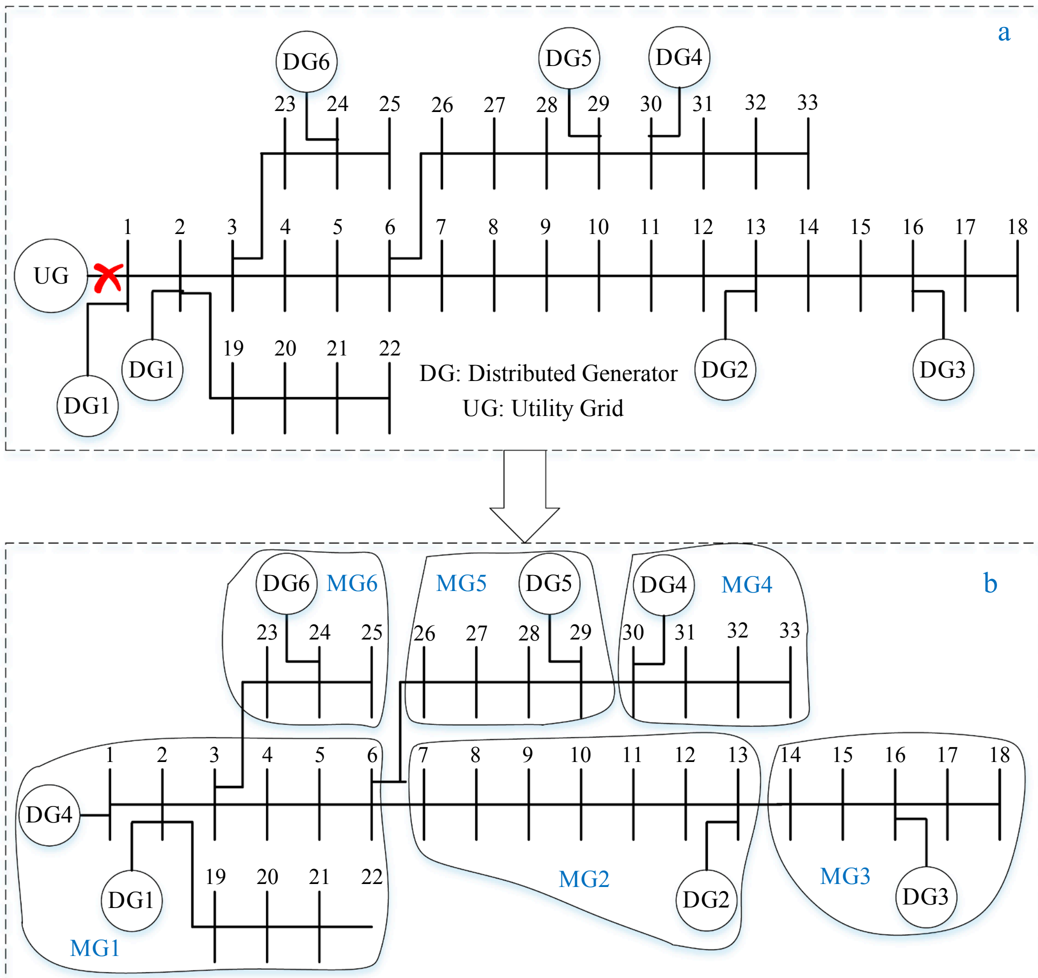

Fig. 9. (a) Conventional distribution system; (b) transformed microgrid network [53].

[60]. However, due to the propagation of events, the generation sources of one or more microgrids may also be compromised. In that case, other healthy microgrids can support the critical loads of the on-emergency microgrids, as shown in Fig. 10b. Therefore, networking of microgrids to enhance the service reliability of consumers is considered as an extended form of the single microgrid concept [61].

Various structured energy management architectures (nesting, intersection, and union) are assessed by [62] and their resilience performances are analyzed. Nested microgrids are suggested by [63] for enhancing the resilience of microgrids in islanded mode. Due to the ability of the nested microgrids to form sub-groups, the resiliency of the disconnected microgrids increases and the probability of forming sub-groups increases with increases in the number of microgrids. Clustering of microgrids to form self-sufficient communities during major disruption events is proposed by [64]. Power sharing among the microgrids of the cluster are considered to assure the self-sufficiency, cost economics, and stability of the network. A network of microgrids having their own local resiliency enhancement algorithm is proposed in [65]. The

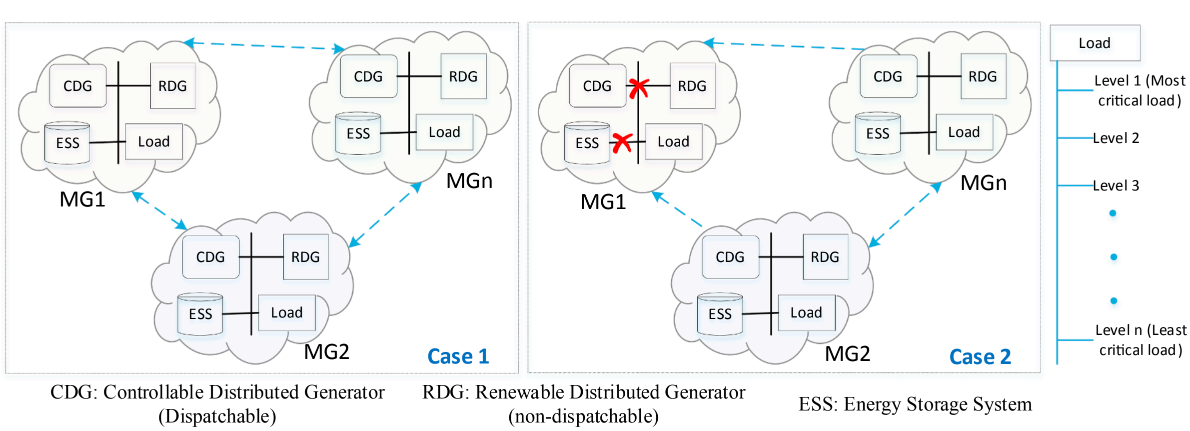

Fig. 10. Networked microgrids in islanded mode: (a) healthy microgrids; (b) MG1 on emergency [60].

concept of adjustable power is adopted in [65] to share the power from cheaper generation sources of other microgrids of the network to fulfill the resiliency requirements of all the microgrids in the network.

A resilient networked microgrid architecture is proposed by[66] for coping with disastrous events. In the normal case, each microgrid owner operates its microgrid for gaining financial interests. However, in emergency situations, they all act as a single entity and collaborate with each other to enhance the resiliency of the network. After analyzing various benefits of networked microgrids, it has been concluded in [47] that networked microgrids are not only beneficial for enhancing the physical resiliency of power systems but are also beneficial for coping with cyber threats.

3.4. Multi-energy microgrids and energy hubs

During natural disasters, not only electrical infrastructure is damaged but also other infrastructures are influenced. This infrastructure damage may either be directly due to the event or may be due to the outage of power. Contrarily, the outage of other networks may influence the power network adversely, i.e communication network and transportation networks. Similarly, due to the outage of power, other energy networks, i.e. heating and cooling networks may also be paralyzed. Therefore, several studies have considered the coupling effect of power network on other networks and overall energy resilience during major events is analyzed. A conceptual framework for analyzing total energy resiliency of urban areas is developed in [67] after reviewing energy resilience-related literature. The economic stability during major events is suggested by [68] in terms of energy provided to the affected areas. In order to assess the economic resilience of the outage area, resilience aspects in the connected disciplines are also analyzed. The lifecycle cost of energy microgrids impacted by catastrophic events is analyzed in [69]. A tool is developed by [70] for giving insight into the optimal mix of technologies (combined heat and power). The tool can simultaneously help increase the resilience of supply while at the same time reduce the emissions.

The coupling between electrical and gas infrastructures during major events and their impact on energy resiliency are analyzed in [71]. In order to assess the resiliency, vulnerable components of both the networks are analyzed and pre-event analysis is performed. The deployment of smart grids in Brazil are reviewed and performance of energy networks during major outage events is analyzed by [72]. The correlation among microgrids, distribution systems, and transmission networks during natural disasters is analyzed in [133]using a mesh grid approach. In [73], development of a multi-energy microgrid is suggested through optimal sizing and siting of tri-generation equipment. An energy hub, as shown in Fig. 11, is suggested to ensure the islanded mode operation of the microgrid under prevailing uncertainties.

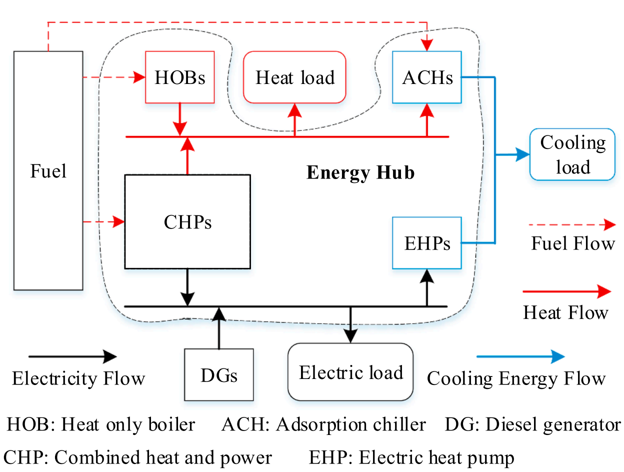

Fig. 11. Schematics of a typical energy hub [73].

The methods available in the literature for enhancing the resilience of power systems by the formation of microgrids are summarized in Table 4. These methods are broadly categorized as the transformation of the conventional power systems into microgrids, the formation of dynamic microgrids, the formation of networked microgrids, and the formation of multi-energy microgrids and energy hubs. In addition to these categorized methods, some other methods are also available in the literature for enhancing the resilience of power system utilizing microgrids or distributed energy resources, as tabulated in Table 4.

4. Strategies used by microgrids for enhancing resilience

Microgrids have the potential to decrease the outage time in power systems by feeding local loads during system contingencies [134], this is known as microgrid formation. As discussed in the previous section, the formation of microgrids during major outage events is a popular research area and plenty of studies are available in the literature. Another research area, which has attracted the attention of the researchers is strategies used by microgrids for enhancing their resilience. Therefore, recently, operation methods used by microgrids for enhancing their resilience are also gaining popularity, as described in the following sections. Similar to the power system resilience methods, the resilience enhancement methods for microgrids can also be divided into three major categories, as shown in Fig. 12. This division is based on the event occurrence and clearance times.

4.1. Proactive scheduling

Microgrids need to prepare for potential events before the occurrence of the events by scheduling their resources in a conservative way [74], i.e. proactive scheduling. History data can be used to predict the occurrence of a particular event and normal operation schedule of microgrids can be revised via resiliency cuts. Resiliency cuts refer to additional resiliency constraints, which are introduced in the original problem (proactive operation phase) to achieve a certain resilience target. These cuts are generally introduced for energy storage elements and reserve procurement to maintain a certain level of energy to enhance the system resilience during contingencies. Resiliency cuts are different from the Benders' cuts, the purpose of later is to avoid infeasibility of the first stage problem by adding primal plane cuts from the second stage problem. However, the purpose of the resiliency cuts is to ensure the predefined resiliency target by cutting (limiting) the original feasible planes of the problem. For example, not allowing the optimization algorithm to discharge energy storage elements below a certain level or limiting the utilization of available fuel above a certain amount. The left part of Fig. 13 shows the flowchart for the resilience enhancement of microgrids in the grid-connected mode, before the occurrence of the event. These operation strategies are known as proactive operation strategies, due to their enforcement before the occurrence of the event.

A proactive operation scheme against extreme floods is proposed in [75], where the vulnerable components of microgrids are identified first. Considering the tripping of these vulnerable components, a proactive operation scheme is employed to reduce the curtailment of loads. In order to avoid the cascading failures, a defensive islanding strategy is proposed by [17] before the occurrence of the event, where a severity index is defined to access the application of defensive islanding. A proactive operation scheme for enhancing resiliency during an unfolding event is proposed in [33], where current and potential future statuses of the system are considered. A two-step operation strategy is proposed by [74] for preparing microgrids against potential natural disasters and assure the feasible islanding of microgrids during the events. A network of microgrids is considered in [65], where each microgrid prepares for potential events

considering its local resilience requirements. The central energy management system enhances the resilience through the adjustable

Table 4
Literature review on formation of microgrids for resilience enhancement.

Category	Major considerations	Reference
Transformation of power systems into microgrids	Optimal siting and sizing of switches for network transformation during events considering investment costs and loss of load during disruptions	[50]
	Reconfiguration of power system during events considering faulty equipment	[51]
	Formation of autonomous microgrid network from a distribution network	[52]
	Decomposition of distribution networks into self-sufficient microgrids for assuring power supply during major events	[53]
Dynamic microgrid formation	Real-time reconfiguration of double bus bar DC system to form resilient microgrids by dynamically dividing load	[54]
	Division of on-outage area into self-sufficient microgrids for self-healing	[55]
	Self-organizing of microgrids via clustering of microgrids dynamically	[56]
	Computation burden reduction algorithm for dynamic microgrid formation	[57]
	A master–slave approach, with one DG as master for formation of dynamic microgrids with self-sufficiency	[132]
Networked microgrid formation	Nesting of microgrids to form sub-groups during emergencies	[63]
	Clustering of microgrids to form self-sufficient communities during events	[64]
	A network of microgrids having their own local resiliency enhancement mechanism and central controller for system resource utilization	[65]
	Design of an operation algorithm for collaborating with other microgrids of the network to enhance the resiliency during emergencies	[66]
Multi-energy microgrids and Energy hubs	Development of a tool for combined heat and power system evaluation in terms of resilience and emissions	[70]
	Analysis of coupling between electrical and gas infrastructures during major events and their impact on energy resiliency	[71]
	Analysis of performance of energy networks during major outage events	[72]
	Optimal siting & sizing of tri-generation equipment for energy hub deployment	[73]
Other methods	A two-step reliability-oriented method for reserve capacity and reliable power supply to consumers	[131]
	Analysis of utilizing microgrids as a local, community, and black start resource	[48]
	The integration of renewable hybrid power systems in a residential district and analysis of reliability of renewables	[76]
	Integration of renewable energy sources in microgrids for enhancing resilience of power systems	[130]

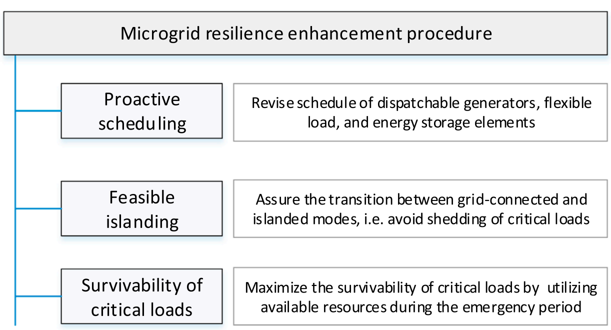

Fig. 12. Overview of microgrid resilience enhancement procedure.

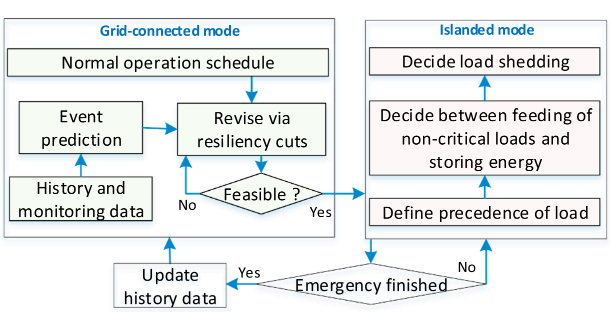

Fig. 13. Resilience enhancement in normal and emergency modes.

power of dispatchable generators of each microgrid. Using the recent history of events, the main features and requirements of resilient microgrids are identified before the event in [76] and an index is proposed to quantify the effectiveness of the proposed method during the event. A sequential attack scenario is considered in [77] and preventive actions are suggested for resiliency enhancement. It has been observed by [77] that sequential attacks result in more severe damages to the network than parallel attacks.

4.2. Outage management

When the event occurs, microgrids need to assure the survivability of critical loads during switching from grid-connected to islanded mode [101], i.e. feasible islanding. This feasible islanding is achieved by using the resiliency cuts as shown in Fig. 13. Finally, microgrids need to feed the critical loads by using local resources only during the islanded period [78], i.e. survivability of the critical loads. Load priorities are defined since all the loads may not be served during emergency periods. Based on these decisions, the load-shedding amount at different load levels is decided. If the emergency is finished, microgrid switches back to the normal mode. Otherwise, scheduling window is updated and the emergency operation is repeated until the end of the emergency period, as shown in Fig. 14. Several operation methods for enhancing the resiliency of microgrids during the islanded period (after the occurrence of an event) are proposed in the literature [79–82].

An emergency demand response method is proposed in [79] for autonomous operation of microgrids during the islanded period. The frequency of the microgrid is also considered during the emergency period to assure the stability of the system. Both centralized and

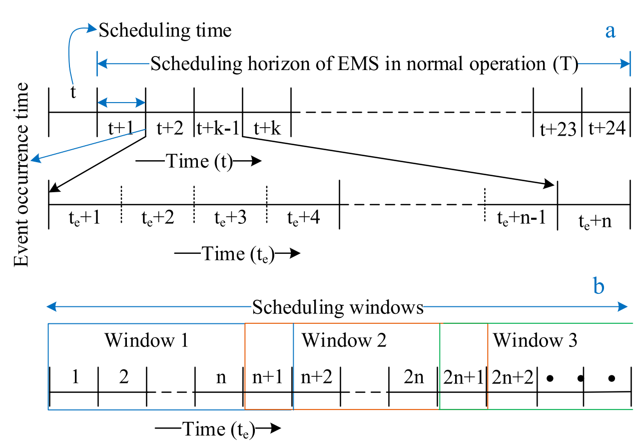

Fig. 14. Scheduling windows of microgrids: (a) normal mode operation; (b) emergency mode operation [101].

decentralized operation schemes are devised by [80] for a pair of islanded microgrids to decide either to couple or not during an emergency event. If the communication system is available, the centralized method is utilized and the decentralized method is adopted if the communication system is compromised. A strategy for deciding the cost of distributed energy sources during emergency operation of microgrids for emergency power services is proposed by [82]. By using the proposed method, survivability of loads is investigated. In [63], load priorities are defined in the islanded microgrids and a strategy is devised for enhancing the survivability of critical loads during an extended period of power disruption. In [135], a resiliency enhancement method is proposed by defining different weights for various load types. In [31,32], the backup systems for emergencies are analyzed and renewable technologies (photovoltaics with battery, fuel cells, etc.) are suggested to avoid curtailment of loads due to unavailability of fuel during emergencies. A two-stage resilience enhancement strategy for microgrids is proposed in [83]. In the first stage, local optimization of individual microgrids is performed. In the second stage, power sharing among the microgrids is considered to enhance the survivability of critical loads of the entire distribution network. The ability of a microgrid to supply critical loads of the upstream distribution network without compromising its local critical loads during a major disruption event is analyzed in [84]. Due to the influence of load and renewable uncertainties on the outage management during resilient operation of microgrids, prevailing uncertainties are considered by [85]. A stochastic method is adopted to realize the uncertainties and the impact of those uncertainties on the resilient operation of power systems is analyzed.

4.3. Advanced operation strategies

Artificial intelligence techniques, multi-agent systems, demand response programs, energy storage systems, and various other advanced operation strategies have also been suggested for enhancing the resilience of microgrids, as described below. A Fuzzy-logic method for resilience enhancement of microgrids is proposed in [86] by only revising the schedule of energy storage elements. A battery operation controller is devised to maintain the target energy level in the battery, as shown in Fig. 15. Energy storage systems are utilized to enhance the survivability of critical loads after major outages in [94]. In addition, dynamic penalty costs and following day operation is also incorporated in the operation model to enhance system resiliency for extended outage periods. Game-theoretic model for renewable generation planning with a focus on microgrid resilience during natural disasters and man-made events is developed by [87]. Multi-agent systems are reviewed by [88] for resilient microgrids considering self-healing capabilities. Demand response and energy storage elements are considered by [89] for enhancing the resilience of microgrids during outages. A model predictive control-based energy management system for isolated microgrids is proposed by [90] for proper dispatch of energy storage elements during outages. Multi-agent systems have been designed by [91–93] with a focus on the power system resilience. In [91] and [92], initially, the set of multi-agent system design principles for resilient power systems are identified. Then, the adherence of prevailing multi-agent systems to these design principles are assessed. In [93], the self-interest of local systems and cooperation interests are used to carry out successfully transitions from normal to emergency modes and vice versa. An autonomous and multi-agent system is proposed in [92] with a focus on design principles that can bring greater resilience to power systems in a decentralized way. The transition of microgrids from grid-connected to islanded mode during major events and back to grid-connected mode are realized in [93] using a multi-agent system. In [95], the impact of demand response is suggested as a potential measure to enhance the service reliability of both critical and non-critical loads during emergencies, especially for microgrids with enhanced penetration of renewables.

4.4. Resilience enhancement methods for AC, DC, and hybrid microgrids

The resilience enhancement mechanism of different types of microgrids, i.e. AC, DC, and hybrid AC/DC, could be different and impact of each type of microgrid on the resilient performance of microgrids could also be different. Therefore, several types of research are conducted for each type of the microgrid, as mentioned in the following paragraphs. An overview of the three microgrid configurations (AC, DC, and AC/DC hybrid) is presented in Fig. 16.

AC network constraints are also incorporated in the resilience-oriented operation scheme proposed by [84] to provide a better solution

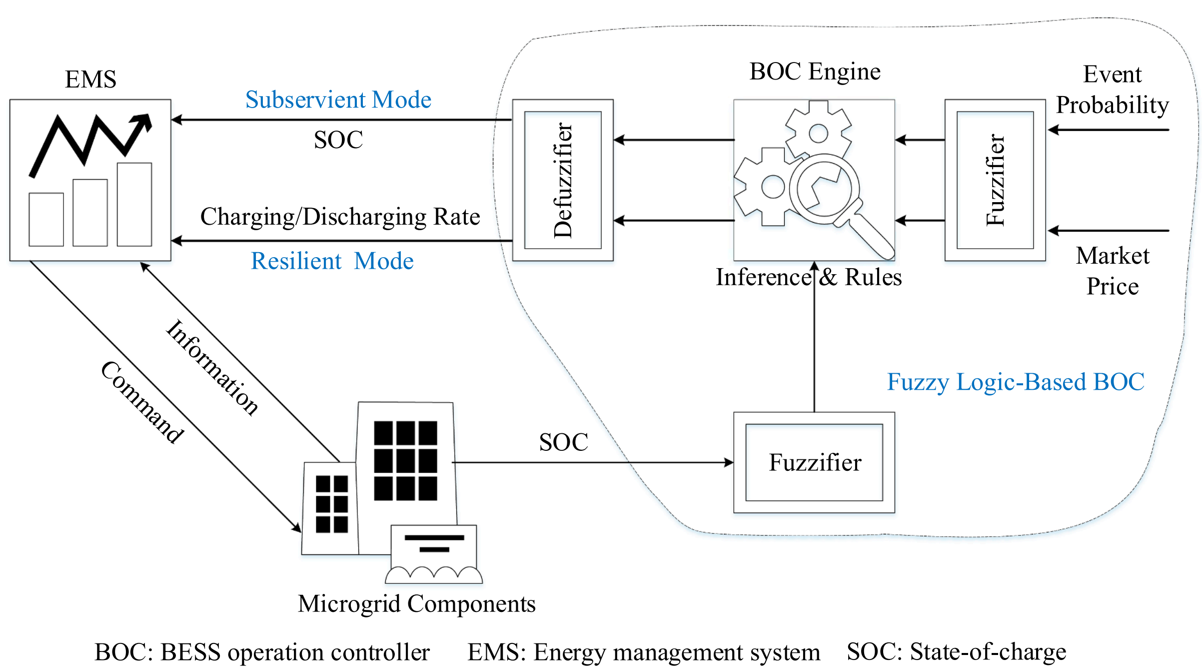

Fig. 15. Resilience enhancement by revising battery schedule via fuzzy logic rules [86].

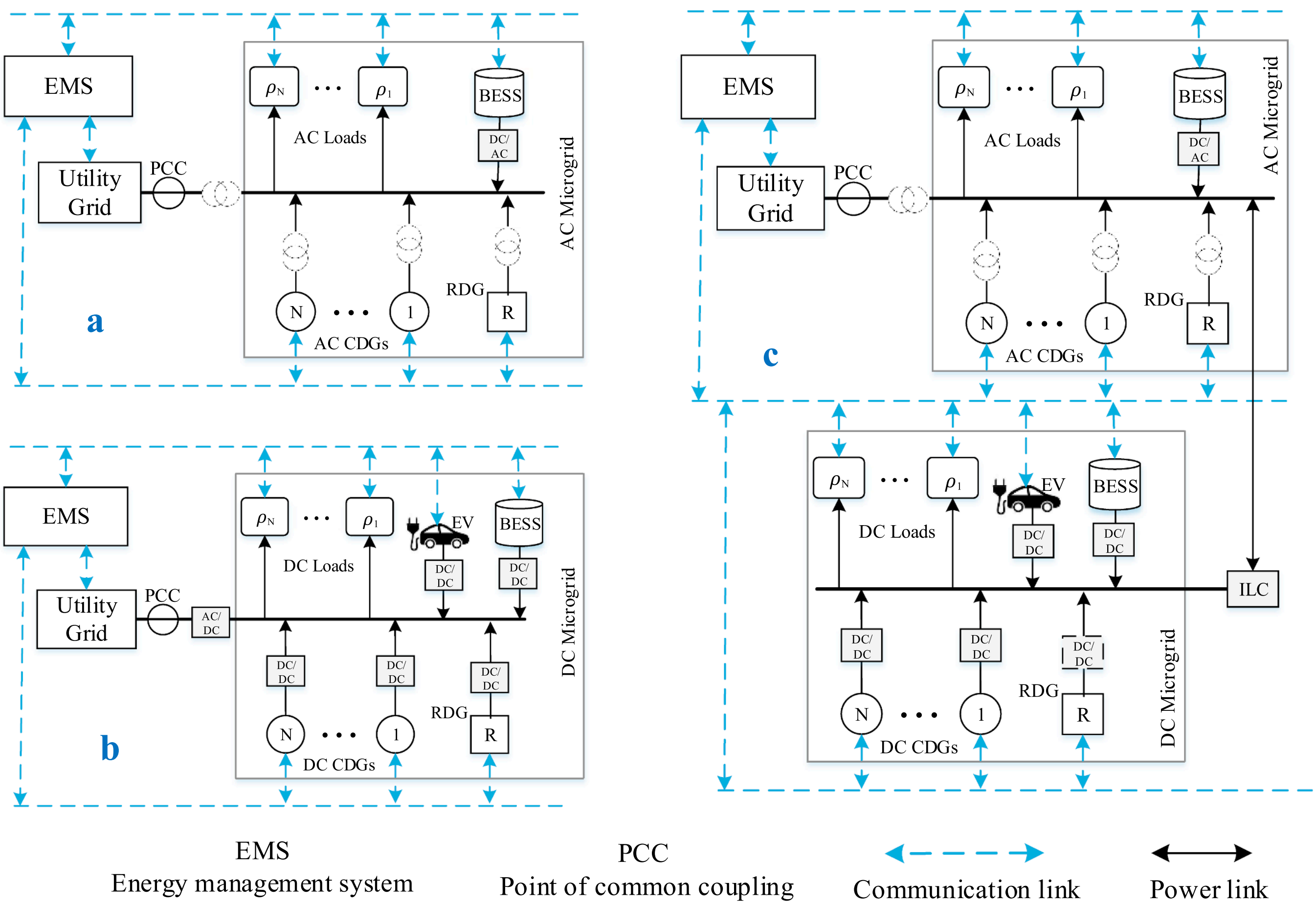

Fig. 16. Configuration of microgrids: (a) AC microgrid; (b) DC microgrid; (c) AC/DC hybrid microgrid.

for the security-constrained operation of microgrids. The resilience of on-outage portion of an AC distribution system is improved by sectionalizing it into self-sufficient microgrids by [55] during major outage events. Microgrid clustering after the occurrence of an event is considered for AC microgrids by [56], where each microgrid can decide to join or leave the cluster based on its local generation/load amount. The effectiveness of load responsiveness and integration of electric vehicles for enhancing the resilience of AC microgrids after the occurrence of any major event is analyzed by [79]. A mechanism to enhance the survivability of critical loads using storage elements is suggested by [78]during extended islanded periods due to natural disasters for AC microgrids.

The authors of [136] and [96] have analyzed the resilient performance of a conventional AC microgrid by transforming it into its DC counterpart. It has been demonstrated that the DC system performs better in terms of resilient response to emergencies and economic operation at steady state. A cooperative network of DC microgrids is considered in [97] for enhancing the resilience during emergencies and an adaptive energy management system is proposed. A double bar bus DC microgrid system is considered in [54], which distributes the load among the two busses dynamically during outages to ensure the self-sustainability of the system. Resilient performance of DC microgrids is analyzed by [98] under communication linkage failure. In addition, a communication islanding detection method is proposed and the operation and stability of DC microgrids are analyzed. The limitations of energy management systems are tested for a network of DC microgrids and resilience discrepancies are analyzed in [100]. It has been concluded that a tradeoff between the system resilience and degradation of batteries need to be determined.

Technical benefits of AC and DC microgrids can be achieved by combining AC and DC microgrid to form a hybrid microgrid, where the AC and DC sides are interfaced by interlinking converters. A load sharing mechanism for AC and DC microgrids is suggested in [60] to ensure the power balance in the system during contingencies. A pilot hybrid microgrid is considered in [99] by using renewable energy sources and storage elements and its ability to feed both AC and DC loads during outages is analyzed. A two-step resilience enhancement scheme for a single hybrid microgrid is proposed in [101], where pre and post-event scenarios are considered. A network of hybrid microgrids is considered in [65] for enhancing the resilience of the network during contingencies and the concept of adjustable power is also utilized.

4.5. Centralized, decentralized, and hierarchical methods

Various network configurations are studied in the literature for enhancing the resilience of microgrids, i.e. centralized, decentralized, and hierarchical energy management systems, as shown in Fig. 17. In a centralized energy management system, all the information is gathered by a central controller and the central controller deals with the external controller (distribution network operators). In the case of decentralized systems, the central controller is not required and all microgrids can directly interact with the external controller. In the case of hierarchical systems, similar to decentralized systems, each microgrid performs local optimization. Then, the surplus/shortage information is updated to the central controller. The central controller is responsible for interacting with the external system, similar to centralized systems. The benefits of each system and available literature on each architecture are summarized in the following paragraphs.

Centralized energy management systems are suggested by various

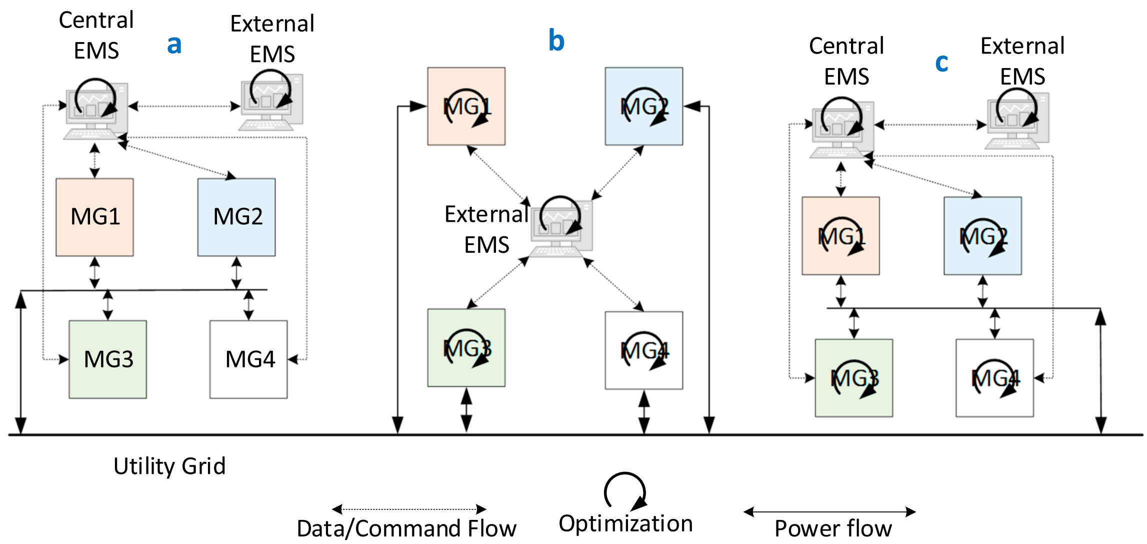

Fig. 17. Overview of energy management architectures: (a) centralized; (b) decentralized; (c) hierarchical [63].

researchers to enhance the resiliency of microgrids due to their ability to better utilize the system level resources, as described below. A centralized energy management schemes for reducing curtailment of critical loads during major outage events by efficiently utilizing available resources is proposed in [74]. Both normal and emergency mode operation schemes for enhancing the resilience of microgrids using a centralized energy management system are proposed by [101]. The outage area is optimally sectionalized into self-adequate microgrids using a central controller by [55] and connection of various microgrids is also considered to form a microgrid network.

The centralized methods may face challenges during the major outage events due to damage of the communication network. Some of the equipment may not be able to communicate with the central controller and failure of the central controller will result in the system collapse. A decentralized self-organizing microgrid architecture is proposed in [56] for islanded microgrids after natural disasters. Formation of microgrids in a radial distribution system after major events is proposed in [57], where only local communication is used to acquire the global information of the system. A distributed and adaptive energy management system is proposed in [97], where microgrids operate in a cooperative fashion to achieve a higher level of resilience.

The decentralized controllers can enhance the resilience of power systems but result in higher operation costs due to unawareness of system level resources. Hierarchical energy management systems are proposed by various researchers, which are a combination of centralized and decentralized energy management systems. A two-level hierarchical energy management system is proposed by [83] for feeding the unserved loads of local microgrids during the first step. A hierarchical energy management system with local and central energy management systems is utilized in [65]for enhancing the survivability of critical loads for a microgrid network. A centralized-decentralized (hierarchical) operation method is proposed in [102], where different control levels are considered and different algorithms are devised for each level to maximize the resilience of the system.

A summary of the methods utilized by microgrids for enhancing their resilience is presented in Table 5. These methods can be broadly categorized as proactive scheduling, outage management, and advanced operation methods. In addition, the resilience schemes for different microgrid types and various microgrid architectures available in the literature are also analyzed. Microgrids are either AC type, DC type, or a hybrid of AC and DC types, i.e. hybrid microgrids. Similarly, the energy management architectures of microgrids can be categorized as centralized energy management systems, decentralized energy management systems, and hierarchical energy management systems.

5. Communication, event-specific, and component resilience

5.1. Communication resilience

In order to assure the resilience of power systems, a reliable and resilient communication infrastructure is also required. The communication requirements of modern power systems in terms of data delivery and real-time monitoring and control are analyzed in [103]. A testbed is developed by [104] for experimentally analyzing the malicious threats to the power systems. Various cyber emergency scenarios including the denial of supervision, manual intervention, and denial of execution are tested.

An adaptive protection scheme is proposed in [105] for enhancing the resiliency of power systems against communication outages, where a super capacitive energy storage system is utilized and an algorithm is developed to decide either to feed the fault currents on the AC side or not. An event-triggered communication scheme is also devised to share the power among the networked microgrids. The objective of the developed network is to enhance the resiliency, elasticity, and efficiency by sharing power in both transient and steady-state periods.

In order to enhance the resilience of communication network in microgrids, software-defined networks are also proposed in the literature. They provide a higher level of abstraction and interfaces for interacting with the communication network of the microgrid. An overview of the software-defined network-based multi-layer architecture for resilience enhancement of microgrids is shown in Fig. 18. A software-defined network is developed in [106] for transforming isolated microgrids into integrated networks. Programmable networks for resilient microgrids are developed by using software-defined networks in [107] and [108]. Both physical and cyber disturbances are considered by [107] and two layers are designed for evaluating the performance of the developed platform. In the upper layer, a cyber layer is developed to expedite the application development of microgrids. In the lower layer, a physical microgrid platform is developed with a focus on high penetration of renewables. A software-defined network-based communication architecture is proposed for enhancing the cyber security and resilience of microgrids by [108]. The developed platform can help in

Table 5
Literature review on methods used by microgrids for enhancing resilience.

Category		Major considerations	Reference
Proactive scheduling		A defensive islanding scheme to avoid cascading failures during events	[17]
		A proactive operation scheme for enhancing resiliency during an unfolding event considering current and future states of the system	[33]
		A two-step operation strategy is proposed for preparing microgrids against potential natural disasters	[74]
		A proactive scheme for extreme floods considering vulnerable components	[75]
		A sequential attack scenario is considered and preventive actions are suggested for resiliency enhancement	[77]
Outage management		Load priorities are defined and a strategy is devised for enhancing the survivability of critical loads during an extended period of power disruption	[63]
		An emergency demand response method for autonomous operation of microgrids during the islanded period	[79]
		Both centralized and decentralized operation schemes are devised for a pair of islanded microgrids to decide either to couple them or not	[80]
		A strategy for deciding the cost of distributed energy sources during emergency operation of microgrids for emergency power services	[82]
		A resiliency enhancement method by defining different load weights	[135]
Advanced operation methods		A Fuzzy-logic method for resilience enhancement of microgrids is proposed by only revising the schedule of energy storage elements	[86]
		Game-theoretic model for renewable generation planning with a focus on microgrid resilience during natural and man-made events is developed	[87]
		Multi-agent systems are reviewed for resilient microgrids considering self-healing capabilities	[88]
		Resiliency enhancement via demand response and energy storage	[89]
		Multi-agent systems have been designed with focus on the system resilience	[91]
Microgrid type	AC	Effectiveness analysis of load responsiveness and integration of electric vehicles for enhancing resilience of AC microgrids after an event occurrence	[79]
		Incorporation of AC network constraints in the resilience-oriented operation	[84]
	DC	A double bar bus DC microgrid system for distributing the load among the two busses dynamically during outages	[54]
		Transformation of AC microgrids to DC microgrids for enhancing resilience	[96]
	Hybrid	A load sharing mechanism for AC and DC microgrids for power balance	[60]
		A two-step resilience enhancement mechanism for hybrid microgrids	[65]
Microgrid architecture	Centralized	Dividing on-outage area to self-adequate microgrids via a central controller	[55]
		Efficient utilization of available resource for reducing curtailment of critical loads during major outage events via a centralized controller	[74]
	Distributed	A decentralized self-organizing microgrid architecture is proposed for islanded microgrids due to natural disasters	[56]
		A distributed and adaptive energy management system to achieve a higher level of resilience via cooperative operation.	[97]
	Hierarchical	A two-level hierarchical energy management system for feeding unserved loads of local microgrids during the first step	[83]
		A hierarchical operation method for self-optimization of islanded microgrids using a multi-agent system	[102]

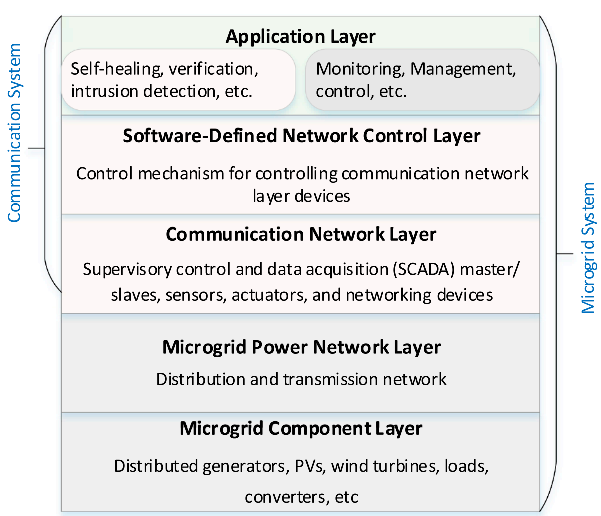

Fig. 18. Software-defined network-based microgrid architecture [108].

designing resilient microgrids by managing, programming, and monitoring the communication network on one hand. On the other hand, it can assist the developers to create applications to dynamically configure and operate the network.

5.2. Event-specific resilience

The causes, prediction level, possible damage, and mitigation strategies for different weather events are different. Therefore, several event-specific analysis and mitigation methods have been proposed [75,109–112]. Machine learning-based prediction methods are suggested by [109–111] for determining the potential damages caused by hurricanes. Two indices for assessing the performance of the proposed method are also developed in [109]. The authors in [110] have additionally developed a predictive tool for assessing the investment methods for enhancing the resilience of power systems after hurricanes. A probabilistic approach is suggested in [111]for quantifying the resilience of power systems against hurricanes and damages caused by hurricanes. A proactive scheduling approach is suggested by [75] to soften the adverse impacts of floods. The vulnerable components are identified first and tripping of all the vulnerable components are considered to incorporate preventive measures. The resilience achieved by household customers via material and social elements during storms are

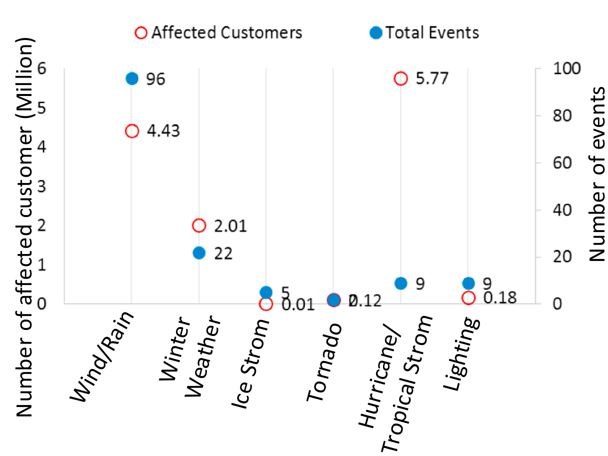

Fig. 19. Major events in the last 4 decades in New Jersey [26].

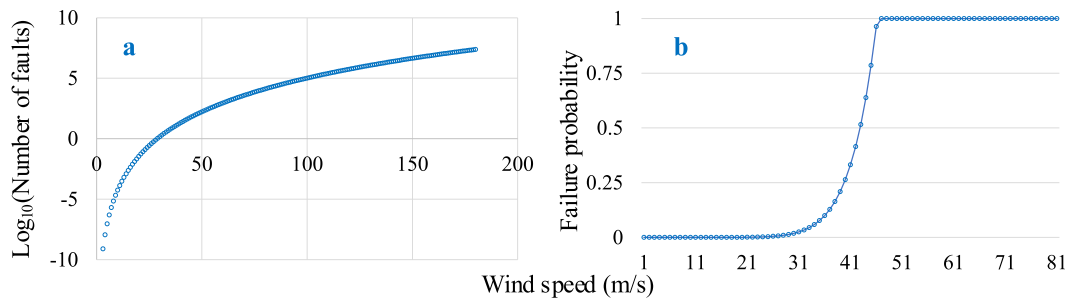

Fig. 20. Wind speed and component outage (a) number of faults (b) line outage probability [113].

analyzed by [112]. In addition, the challenges faced and strategies adopted by various consumers during the major outage due to storms are also outlined. An overview of the major events occurred in the last four decade in New Jersey are shown in Fig. 19 and impact of each event type are also presented [26].

5.3. Resilience of power components

In addition to studies on strategies adopted by microgrids for enhancing their resilience, studies on the resilience of particular components are also available in the literature. The failure of a distribution line and its impact on the resilience of a microgrid is analyzed in [113], where fragility curves are utilized to predict the line failure. The line outage data of UK's distribution system against wind speed is used in [113], as shown in Fig. 20. A handbook on analyzing the reliability of power electronic equipment is drafted by [114], where both part stress and part quantity analysis methods are presented. The solar irradiance and ambient temperature-based thermal analysis are proposed for photovoltaic array modules in order to determine the additional temperature rise in the components induced by the operation outside feed-in hours by [115]. Thermal stress and stability of power converters during major power outage events are analyzed in [116] by combining both of the collected field data of wind generation and load demand levels.

An overview of the communication resilience enhancement methods, resilience enhancement methods for specific events, and resilience enhancement of power system components are presented in Table 6. In case of communication resilience, the software-defined network-based resilience enhancement methods are focused due to their ability to provide a higher level of abstraction and interfaces for interacting with the communication network. In the case of event-specific analysis, proactive and survivability enhancement schemes and resilience analysis methods specific to particular events, i.e. floods, hurricanes, and storms are analyzed. Finally, in case of component-specific resilience analysis, the resilience of power distribution lines and towers against extreme winds are analyzed. In addition, the resilience of power converters and photovoltaic cells are analyzed, as shown in Table 6.

6. Research gaps and future directions

6.1. Research gaps

Resilience analysis and enhancement is an inter-disciplinary research and it is a spatiotemporal problem. Natural disasters may not only destroy the power network but they may also destroy other networks like gas, communication, and transportation, which will adversely influence the power network. Most of the studies available in the literature focus on one of the aspects of power networks while ignoring the influence of other closely related structures. Therefore, multi-disciplinary research is required to quantify the impact of events, develop resiliency enhancement strategies, and expedite the restoration process.

In order to prepare the microgrids for potential events and enhance the hardening of power systems against these major disruption events, accurate event forecasting and damage estimation methods are required. Most of the event forecast and damage estimation methods available in the literature are based on local data only and focused on a particular event thus making it difficult to apply for future events and in other localities. Therefore, more accurate and generalized methods are required using data from various localities, which can be achieved by using big data analysis and deep learning methods.

In addition to the formation of microgrids after disruption events, microgrids need to be prepared for these major events before the occurrence of the event. If microgrids are not prepared for these events, before the occurrence of events, the feasible islanding and survivability

Table 6
Literature review on methods for communication, event-specific, and component resilience.

Category	Major considerations	Reference
Communication resilience	A testbed is developed for experimentally analyzing the malicious threats to the power systems	[104]
	An adaptive scheme is proposed for enhancing the resiliency of power systems against communication outages	[105]
	A software-defined network is developed for transforming isolated microgrids into integrated networks	[106]
	Both physical and cyber disturbances are considered and two layers are designed for evaluating the performance of the developed platform	[107]
	A software-defined networking-based communication architecture is proposed for enhancing the cyber security and resilience of microgrids	[108]
Event-specific analysis	A proactive scheduling approach to soften the adverse impacts of floods	[75]
	Machine learning-based prediction methods for determining the potential damage caused by hurricanes	[109]
	A resiliency enhancement method and two indices for assessing the performance of the proposed method during hurricanes	[110]
	A probabilistic approach for quantifying the resilience of power systems against hurricanes	[111]
	The resilience achieved by household customers via material and social elements during storms are analyzed	[112]
Component resilience	Fragility curves-based resilience analysis of microgrids	[113]
	A handbook on analyzing the reliability of power electronic equipment	[114]
	Impact of operation outside feed-in hours on PV modules during events	[115]
	Analysis of thermal stress and stability of power converters during major outage events considering field data of wind generation and load demands	[116]

of critical loads could not be guaranteed during the operation mode-changing phase. Therefore, proactive operation strategies are required to prepare the microgrids for a potential event, absorb the impacts of the event, and control the performance degradation during the events.

In order to reduce the computation burden and assure the stability of the system, equivalent microgrid models are developed and utilized for simulations in the literature. Several types of research are available on measured data-based equivalent modeling [137] and dynamic equivalent modeling considering preservation of structure [138] and component flexibility [139]. In addition, studies on order reduction of high fidelity models [140] and generalized dynamic models [141] are also available. The equivalent models may cause loss of information and the required resiliency level may be miscalculated during the estimation phase. Similarly, the expected resiliency may not be achieved during the emergency operation due to lower fidelity modeling of microgrid components. Therefore, the equivalent modeling may result in a difference in the expected and actually achieved resilience during the outages.

6.2. Future directions

Although plenty of literature is available on strategies for enhancing the resilience of power systems and microgrids. There are still several challenges, which need to be considered and incorporated into operation models to better estimate and achieve the desired level of resilience during the major events. Some of these challenges and potential solutions are summarized as following.

- The event occurrence and clearance times are not known in advance and conservative solutions may result in higher operation cost. Therefore, event occurrence probability and damage estimation models need to be incorporated in the operation model. Information from meteorological agencies regarding events, especially weather-related events, can be utilized to estimate the occurrence time of events.
- Energy storage elements are widely used to enhance the resiliency of microgrids. However, simplified models are used in the upper control level and internal dynamics are ignored to estimate the state-of-charge of these storage elements. This results is discrepancies in the state-of-charge of the energy storage elements and ultimately the required resiliency may not be achieved in real situations.
- Higher penetration of renewables can enhance the resiliency of microgrids during disruption of the main grid. However, the intermittent nature of renewables poses more challenges to the operators. Therefore, more robust uncertainty handling methods need to be incorporated in the operation model to assure the required resiliency upon the occurrence of any event.
- Most of the researches focus on a scheduling horizon of one day and resilience algorithms are formulated accordingly. Off-the-horizon resiliency is not considered and it may result in the shedding of critical loads in the following day while feeding lesser critical loads in the current day. This situation becomes worse if only renewable resources are available. Therefore, the generation/consumption profiles of the following days need to consider in the current day and energy storage elements can be scheduled accordingly.
- Realistic assumptions need to be made in accordance with the nature of the event. Some examples could be an interruption in the fuel supply to dispatchable generators during natural disasters, inability to carry out restoration process during storms and floods, damage of remotely controlled switches, etc. These considerations need to be included in the resilience-oriented operation model to get more realistic results.
- During natural disasters, the communication network may be compromised and even some of the components may also disconnect from the microgrid. Therefore, centralized energy management systems and fixed microgrid topologies may not be suitable for resilient operation. Decentralized energy management strategies and ad-hoc microgrids with plug-and-play ability need to be considered.
- Equivalent microgrid models may result in lower computation time and assure the stability of the system but this approximation/simplification may result in erroneous results in terms of system resiliency. The target resilience may not be achieved due to the difference in the equivalent model and the real system and/or due to the wrong estimation during preparation phase using lower fidelity models. Therefore, higher fidelity models need to be considered for computing resilience.

7. Conclusion

The resilience enhancement strategies for power systems available in the literature are analyzed in this paper. The role of microgrids in enhancing the resiliency of power systems by forming self-sustainable microgrids and networked microgrids are analyzed. Similarly, the formation of dynamic microgrids along with the formation of multi-energy microgrids and energy hubs are also analyzed. In addition, the resilience of communication networks and resilience of microgrid components are also investigated. However, interdisciplinary research is required to quantify the impact of major events and design resiliency enhancement strategies for the future. In addition to microgrid formation, strategies utilized by microgrids for enhancing their resilience during various phases of the major events are also analyzed. The available strategies used by microgrids for enhancing their resilience can be categorized as proactive operation strategies, feasible islanding, outage management, and advanced operation methods. Finally, resilience enhancement strategies based on microgrid architectures and strategies used by different types of microgrids for enhancing the resilience are analyzed. Event occurrence time prediction, errors in state-of-charge estimation, uncertainties in renewables, higher fidelity microgrid models, and realistic assumptions need to be considered in the resilience-oriented operation models.

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