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Microgrids for power system resilience enhancement

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ABSTRACT

Power system resilience is defined as the ability of power grids to anticipate, withstand, adapt and recover from high-impact low-probability (HILP) events. There are both long-term and short-term measures that system operators can employ for resilience reinforcement. Longer-term measures include infrastructure hardening and resilient planning, while short-term operational measures are applied in the pre-event, during-event and post-event phases. Microgrids (MGs) can effectively enhance resilience for both transmission and distribution systems, due to their ability to operate in a controlled, coordinated way, when connected to the main power grid and in islanded mode. In this paper, MG-based strategies for resilience enhancement are presented, including MG-based resilient planning and MG-based operational measures, consisting of preventive MG scheduling and emergency measures and MG-based system restoration. Classification of literature is made by considering whether the transmission system, distribution system or individual MG resilience is targeted. The way uncertainties are handled by various methods is also outlined. Finally, challenges and future research requirements for improving MG-based power system resilience are highlighted.

KEYWORDS

Natural disasters, resilience, microgrid, distributed energy resources, resilient planning, operational measures for resilience.

Natural disasters pose serious concerns to human lives and the economy, and they constitute one of the greatest threats to electricity systems[1]. The effects of climate change are increasing both the frequency and the intensity of such incidents worldwide[2,3], as witnessed by several disastrous phenomena. For example, in 2008, Hurricane Ike led to power outages, lasting for several weeks, for almost 2.8 million consumers, provoking huge economic damages[4]. In 2012, Hurricane Sandy destroyed electricity networks, provoking explosions of many transformer substations that caused long power outages for millions of consumers[5]. During the disastrous 2018 California Camp Fire, sparked by a power line, 84 people were killed and the residential property damage alone is estimated to be about $9.3 billion[6]. That event led to Pacific Gas & Electricity (PG&E) bankruptcy[7,8]. In 2021, a series of destructive wildfires erupted in northern Evia in Greece, with over 50,000 hectares burnt, including forests, cultivable land and dozens of homes. Seven medium-voltage lines were destroyed affecting 13,000 consumers[9,10].

Such extreme events occur rarely, but they have serious effects on the power systems[11]. For this reason, they are commonly termed as high-impact low-probability (HILP) events. The ability of the system to anticipate, withstand, adapt and rapidly recover from HILP events, including natural disasters and man-made malicious cyber[12] or physical attacks, is defined as power system resilience[13]. It should be noted that the concept of resilience differs from conventional reliability, which deals with typical failures[14].

Power system resilience is analyzed as a function of time. Considering the time of the HILP event occurrence, a power system might go through different states that compose the *resilient trapezoid model*. This is used for its quantitative resilience assessment[15]. The trapezoid consists of the pre-disturbance resilient state, the state during disturbance progress (when the event occurs), the post-disturbance degraded state (after the event and before the initiation of restoration), the restorative state and the post-restoration state, when the power system is fully restored and operates under normal conditions, as graphically illustrated in Figure 1[15]. Phases I, II and III represent the resilience response to a HILP event which depends on the resilient readiness of the system at the pre-event state. This division is based on the event occurrence and clearance time and is used to classify the resilience enhancement measures for each phase. In the pre-event phase, both long-term and short-term measures can be taken. The distinction between long-term infrastructure hardening measures and short-term smart operational measures to enhance power system resilience is needed at this point[11]. Apropos of long-term resilience boosting measures, power system infrastructure upgrades, like network hardening and reconstruction programs[16,17] and undergrounding of cables[13], should be considered during power system planning. Such measures, as well as vegetation control and management[18], asset inspections (transformers, insulators, line terminals)[19,20], etc., are activities that cannot be implemented within a few hours (or even days), and thus they are categorized as long-term measures and belong to the pre-event planning state. When potential day-ahead extreme events are forecasted and expected to disrupt power systems or have already disrupted the normal operation of the system, smart operational measures might need to be applied. Such measures are essentially short-time, for instance, they involve, among other, generators' re-dispatch, isolation of vulnerable parts of the network, in order to avoid cascading events, public safety power shut-offs, etc. A few hours before the event, the system operator should take preventive measures to enhance power system resilience (mostly day-ahead measures) and by the time the event hits the network and unfolds, the operator must apply corrective operational measures (Phase I). When the event ends, emergency coordination of power system resources and mobilization of repair crews are needed (Phase II). During the restorative state, the coordination of power system resources and damage repair is critical to implement control schemes for the re-connection of

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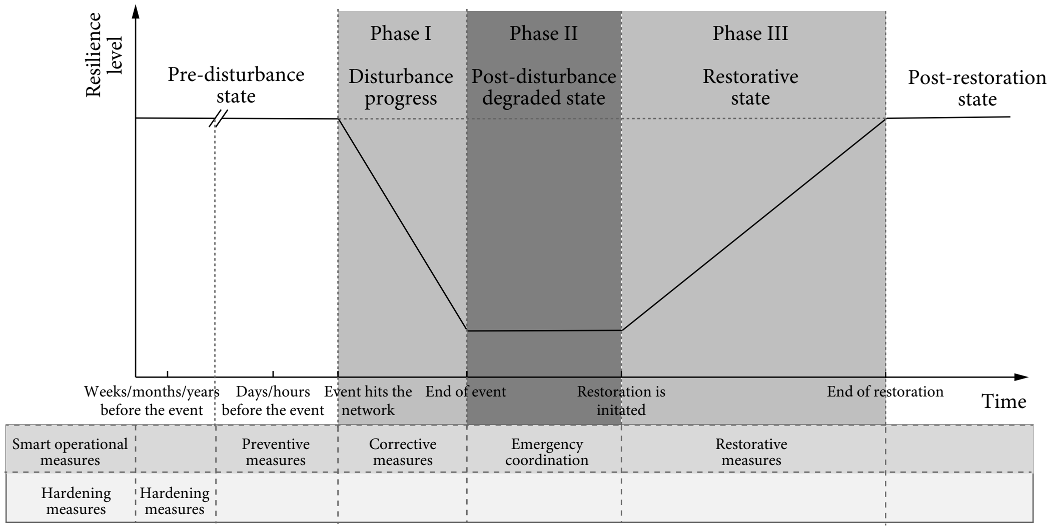

Fig. 1 Resilience trapezoid associated to a HILP event[15].

customers that have experienced blackouts or load curtailments (Phase III).

It should be noted that although operational measures can be implemented in a short time period, they might require longer term investments e.g., installation of sophisticated weather forecasting stations, advanced GIS and PMU-based situational awareness systems, purchase of mobile generators and batteries, use of drones and application of image processing techniques for extended equipment inspections, etc. In fact, advanced situational awareness systems are very important to detect the upcoming threat, estimate its spatiotemporal impact on the system and determine the optimal operational measures to be taken. In most cases, hybrid measures, a mixture of short-term and long-term measures, are the most effective way for a power system to successfully cope with extreme events, depending on power system characteristics and the investment budget.

Microgrids (MGs), thanks to their ability to operate in a controlled, coordinated way, while transferring from grid connected to islanded mode[21,22], constitute an effective resiliency resource, both for transmission and distribution systems[23,24], in all states presented in Figure 1[15]. Distributed energy resources (DERs), microturbines (MTs), wind turbines (WTs), photovoltaics (PVs), energy storage systems (ESSs), flexible loads (FLs), etc., usually compose MGs' critical units[9,25,26]. During extreme events, DERs can sustain customer loads when MGs operate in islanded mode or act as a resource of the upward system[27]. They can also expedite bottom-up service restoration after the damages[25]. MG's concept of locally generating, storing and controlling energy instead of relying on long transmission lines can decrease the vulnerability of the network, improving, at the same time, its resilient response and restoration time[21].

Figure 2 illustrates how MGs can be exploited to enhance transmission and distribution system resilience and how individual MG resilience is strengthened.

Transmission system resilience enhancement: In case of multiple line failures in the transmission system and isolation of part of it, MGs connected to the transmission system directly (MG1) or MGs connected to the downstream distribution system (MG2–MG4) can act as power resources to feed the demand of the isolated part (transmission and distribution system) locally and minimize load shedding. The dashed arrows show the direction of power from MGs to the distribution and transmission systems and indicate that MGs act as power resources.

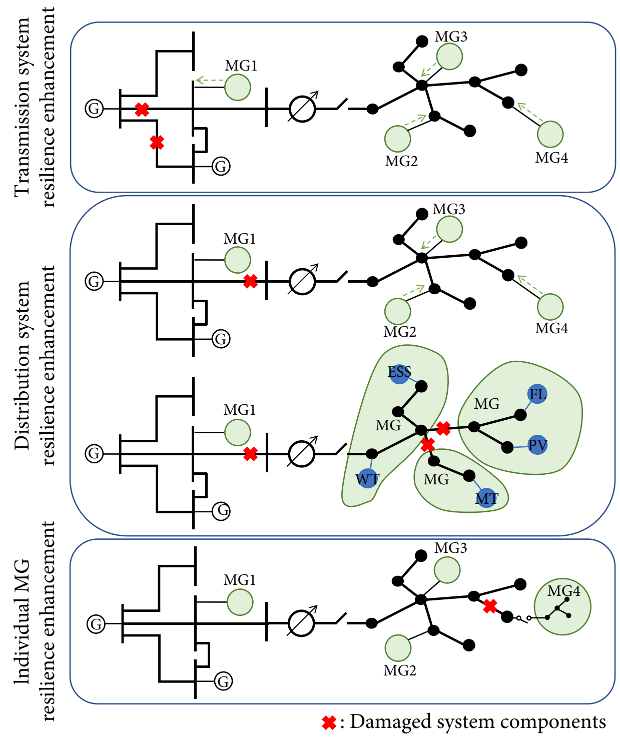

Fig. 2 Transmission and distribution resilience enhancement using MGs and individual MG resilience enhancement.

Distribution system resilience enhancement: In case of isolation of the distribution system due to a failure, MGs connected to the distribution system (MG2–MG4) can act as power sources to meet locally the demand of the distribution system. In addition, when multiple failures occur in the distribution system, it could be sectionalized into self-adequate MGs utilizing the multiple DERs connected in order to minimize load shedding.

Individual MG resilience enhancement: When a failure in the distribution system leads to the isolation of the MG (MG4), it can operate in islanded mode by scheduling properly its resources to serve at least its critical load.

The formation and operation of MGs to boost power system resilience requires both investment-planning measures and advanced operational (smart) measures. Both types of measures should take into account the uncertainties brought mainly by the stochastic nature of renewable energy resources and the potential damages in the event of external threats. In fact, MGs can play a crucial role in all three states of the resilient trapezoid in Figure 1. Some real examples of microgrids supporting the system resilience during Phases II and III have been documented in the literature. The applicability of MGs in resilience enhancement has been also analyzed in a number of publications during the last years. These publications deal separately with MG-based resilient planning (long-term measures, pre-disturbance state), preventive and emergency MG schemes (short-term operational measures, on-event and post-event, respectively) and MG restoration techniques (operational measures, post-event restorative state). Moreover, a number of survey papers have been published dealing with MG-oriented power system resilience. For example, ref. [23] addresses different MG-based resilience scenarios, objectives, metrics and control methods for distribution systems resilience enhancement. Ref. [28] reviews methodologies for the operation and control of networked MGs (NMGs) for improving grid resilience, robustness and efficiency. Various proactive strategies, outage management and advanced operation methods for resilience improvement are described in ref. [22], focusing on self-sustainable, networked and dynamic MG formation frameworks. None of these papers, however, provides a detailed classification of MG-based resilience enhancement methods, for all phases that a system might reside (Figure 1) during the evolution of a catastrophic event. Information about the MG contribution on the system level (transmission, distribution or individual MGs) and the way uncertainties are treated is also missing. It should be noted that multi-energy MGs consisting of DERs combined with cooling, heat and power (CCHP) plants to simultaneously provide electricity and thermal energy supply can substantially increase the flexibility and efficiency of MGs and potentially enhance their ability to enhance the resilience of the system[29]. This is an area that needs to be further researched and has not been particularly considered in this review.

The purpose of this paper is to provide a systematic classification of the published methods relevant to the application of MGs to enhance power system resilience by filling the above gaps. Its main contributions can be summarized as:

- Classification of MG-based measures and actions for resilience enhancement based on the time applied associated with the phases of the resilience trapezoid.
- Presentation of methods, strategies and the basic objective functions for MG-based resilience enhancement categorized in planning, preventive scheduling and emergency operational measures and restoration methods.
- A distinction of methods based on whether they address distribution, transmission system or individual MG resilience.
- A distinction of methods is based on the way they consider uncertainties (deterministic, stochastic and robust) and a short presentation of modeling failure events.
- Directions for future work and tendencies in MG-based power system resilience enhancement.

The rest of the paper is organized as follows: Section 1 presents real-world examples in which MGs played a crucial role in resilience enhancement. Section 2 describes how MGs' general functionalities contribute to power system resilience improvement in the various phases depicted in Figure 1. Section 3 provides a more detailed description of the methods used and categorizes them according to their application at the transmission, distribution or individual MG levels and the way they model uncertainty. Section 4 concludes the paper and identifies research gaps and ideas for further research in MG-based power system resilience strengthening.

1 Real-world examples

This section reviews a number of major natural disasters, in which MGs have played a significant role in resilience enhancement. This has been achieved by satisfying locally some of the power demand, relieving the system stress, thus avoiding large-scale blackouts, and facilitating contingencies handling and service restoration. It also shows cases where individual resilient MGs have withstood severe disruptions and served efficiently local power demand in actual extreme events.

1.1 The Sendai microgrid during and after the tsunami and large-scale earthquake in Japan

On March 11, 2011, a tsunami and large-scale earthquake struck the Tohoku area and caused severe damage to many cities and towns in Japan. The Sendai MG, depicted in Figure 3, is designed as an ideal power supply system that can simultaneously provide services with multiple power quality levels. The MG was developed by NTT Facilities and was installed on the campus of Tohoku Fukushi University in Sendai City. It is an integrated 1 MW power system consisting of power electronics equipment, storage batteries and distributed generators (gas engine generators, solar cells and fuel cells)[30]. It can easily interconnect and disconnect with existing utility power grids. In normal operation, the Sendai microgrid is connected to the utility's grid and improves the level of power quality for the hospital, welfare care facilities and university buildings on the campus. It can disconnect from the utility grid after a power outage and continue supplying power to essential loads or facilities without interruption.

Fig. 3 The Sendai microgrid (Source: NTT Facilities).

After the 3/11 disaster, services continued to be supplied with high quality power by using the energy from solar cells and storage batteries. In addition, since the gas supply network in the city of Sendai was intact, the gas engine generators could perform blackout restart after a power failure at the utility grid and function as the main power supply of the MG. Moreover, the gas engine generator sets and fuel cells of the Sendai MG worked as combined heat and power (CH&P) to produce both electric power and heat for hot water and space heating[30]. Thus, the Sendai microgrid ensured that many patients in the hospital, in the medical and welfare buildings were able to survive and maintain their health.

1.2 Blue Lake Rancheria microgrid against wildfires

A series of major wildfires have repeatedly hit the state of California, especially during the last decade. Due to the disastrous results of these wildfires, distribution companies started to deploy measures to efficiently harden the grid and find ways to preventively enhance its resilience. Blue Lake Rancheria (BLR) region of Humboldt County in California has a demonstration MG that includes 420 kW of PVs, a 500-kW/950-kWh battery bank and a 1-MW backup generator, all connected to the PG&E distribution grid at 12.5 kV, through a computer-controlled circuit breaker, as depicted in Figure 4[31]. A second MG is also formed by a fueling station and an attached convenience store, including PV, batteries and some building system controls. Although the main MG was not initially introduced as a preventive measure against wildfires, it was eventually pushed to that direction, because of the utility's objective of enhancing resilience against outages and potential cost savings, estimated up to 200,000$/year[10]. So, despite the application of public safety power shut-offs during extreme conditions, customers connected to MG retained access to power. In that way, the BLR MG strengthened resilience against outages and contingencies of the bulk transmission system, supporting actions of wildfire risk mitigation. Also, the Blue Lake event center and the hotel can provide shelter to evacuees in an emergency situation[32]. The hotel MG was first activated when islanded against a small bush fire in 2017 and acted as a medical center for patients, a command center for emergency crews and a shelter for evacuees. During the wildfire of October 2019, BLR's MG is estimated to have saved 4 human lives and served about 10,000 people, equal to 10% of the country's population. Californians had recognized the importance of deteriorating fire risk, so the California Public Utilities Commission (CPUC) established exemplar MGs, such as BLR, that can reinforce the grid resilience before the summer of 2020[32].

Fig. 4 Overview of the BLR community microgrid (Source: Schatz Energy Research Center, Humboldt State University)[31].

1.3 Texas microgrids against winter storms

In February 2021, a very strong winter storm has hit Texas, causing rolling blackouts that led more than 4,300,000 citizens to lose access to electricity for hours or even days[33]. The unusual and severe cold resulted in a major power demand rising up to a new winter peak of 69,222 MW. As large power plants began to the trip-off line due to the severe rise of demand and extreme cold and many wind farms lost their productivity, as their turbines succumbed to icing, the electric demand exceeded the available supply, raising the fear of wide-scale blackouts throughout the power system. Utilities were forced to begin controlled blackouts and shut down circuits to many customers, to reduce demand in order to ensure hospitals and other emergency services receive power, while power plant operators struggled to bring their units back online. Despite the small number of MGs in Texas, at this time of major disruption, they managed to alleviate some amount of power demand, combining heat and power, relieving stress on the main grid and extending its capacity. In addition, MGs vital aid managed to provide power to hospitals, stores and shelters during the crisis, mitigating its catastrophic humanitarian and economic impacts and anticipating a total power system blackout. Figure 5 illustrates a grocery store in Texas that remained unaffected by the surrounding power outages, thanks to the MG installed[33].

Fig. 5 Grocery store in Texas that retained power supply by a microgrid during the winter storm (Source: Courtesy of Enchanted Rock)[33].

1.4 Louisiana microgrids against hurricanes

The state of Louisiana has experienced two major destructive hurricanes (both category 4 hurricanes) during the last years, i.e., Hurricane Laura, in August 2020 and Hurricane Ida, in August 2021. MGs played a significant role in keeping the electricity flowing for their customers during Ida, providing power to stores, distribution centers, data centers and water municipalities, while the main grid was knocked by the disaster, inducing 1,200,000 people to lose access to power[34]. Indicatively, after three days into the storm, the local utility managed only to restore electricity to 167,000 customers[34]. PowerSecure Inc. had 15 permanent MG installations as well as 23 mobile MGs in the storm's path, most of them with a capacity of 1,250 kW. A year earlier, PowerSecure Inc. MGs withstood a frontal attack from Hurricane Laura even when the backside of its eyewall went over them. MGs managed to operate during the power outage, feeding crucial community structures that procured shelter, food, water, medicines and other essentials for citizens. An example of such a community distribution center in Pointe-Au-Chien is depicted in Figure 6[34].

1.5 Haiti microgrids against earthquakes

A devastating 7.2 earthquake hit Haiti in August 2021, killing 2, 200 people and destroying up to 55,000 homes[35]. After the event, the 100 kW community MG in Les Anglais was temporarily de-energized to check for downed wires. Given the magnitude of the destruction, the fear of not being able to rapidly repair the damages and re-energize the MG was derived, while awaiting potential aftershocks. Fortunately, the MG, depicted in Figure 7[36], consisting of PVs, a diesel generator and storage units did re-energize and

Fig. 6 Pointe-Au-Chien community distribution site that retained power supply during Hurricane Laura (Source: Courtesy of Footprint Project)[34].

Fig. 7 Les Anglais solar microgrid in Haiti[36].

was able to provide power to a cell tower, allowing residents to reclaim access to electricity and to hold funerals for those who died in the earthquake. A 95 kW MG in Tiburon, a small fishing town in the southern peninsula of Haiti, also operated during the disaster, providing power to 1,200 people and surviving the earthquake with no visible damages[35]. Due to the critical role of MGs during the disaster, interest is raised in installing more community MGs in different regions of Haiti and expanding the ones of Les Anglais and Tiburon, by adding more DERs to extend their capacity in order to serve more people.

1.6 The Kythnos microgrid during natural disasters

The Kythnos microgrid was installed in 2001 in the Gaidouromantra valley (Figure 8), forming probably the first MG in Europe supplied by 100% renewable generation most of the year[37]. The system was built in the framework of European projects, for the electrification of 12 vacation houses in a remote settlement. The generation system consists of seven distributed PV arrays with 11 kWp total installed power and two lead-acid battery banks: one with a nominal capacity of 1,000 Ah/48V (main) and the second one of 480 Ah/60V (secondary)[38]. The main system is managed through three single-phase battery inverters (SMA-SI5048), which forms the three-phase power supply. The secondary is managed through one single-phase inverter (SMA-SI4500) for the power supply of communication and control systems. A three-phase diesel generator of 9 KVA was also installed as a back-up supply, in case battery charging is very low. A system house of 30 m^2 was built in the middle of the settlement to house the battery inverters, the battery banks, the diesel genset and its tank, the computer equipment for monitoring, and the communication hardware.

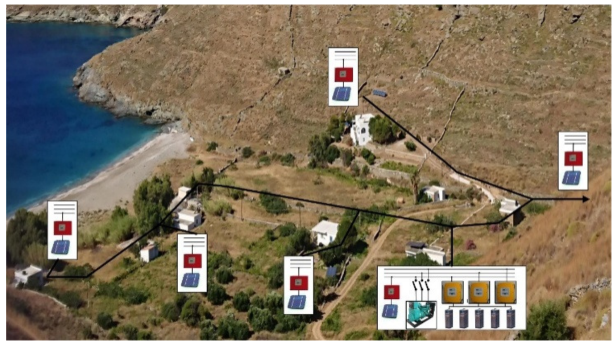

Fig. 8 Overview of the Kythnos microgrid[37].

Throughout the years of its operation, the installation sustained and overcame one severe water flood due to very heavy rain that destroyed and covered with rocks and earth yards, plants and rock partition walls between plots. The MG did not suffer any damage and continued its operation supplying the loads. In June 2012, a wild bush fire spread in the southern part of the island, passed through the valley and destroyed two houses, a PV array and one wooden pole of the electrical grid[38]. The system started to operate two days after the fire, by the time faults were cleared. The PV installation was replaced and the houses were rebuilt.

In the following sections, the various methods proposed for the planning and operation of microgrids to support power system resilience are systematically organized and overviewed.

2 Planning and operational measures for resilience enhancement using microgrids

The measures identified in the introduction can be associated with the three states of the resilience trapezoid as follows: The pre-disturbance hardening state corresponds to the resilient planning phase, a few hours (days) prior to the event occurrence until its ending corresponds to the phase of the resilience preventive, corrective and emergency operational measures and the post-disturbance restorative state corresponds to the system's restoration process. This section describes briefly the contribution of MGs to the aforementioned states.

2.1 Resilient system planning

The resilient system planning problem concerns the economic feasibility of formulating MGs to achieve optimal power generation from DERs considering potential HILP events[39]. This phase includes MG design aiming at optimal resilience-oriented DG placement, low investment cost and optimal utilization of mobile generation resources if needed. Several references consider resilient-based planning, using MGs, e.g. refs. [40–49].

2.2 Resilience-oriented preventive and emergency operational measures

MGs can strengthen resilience when exploited and used efficiently in preventive and emergency modes. It is crucial that MGs optimally schedule their resources and storage capacities in order to be prepared for potential events[50]. MG optimal DER scheduling and defensive islanding constitute the main preventive and emergency strategies. Via resilient-based preventive scheduling, MGs adapt the commitment of dispatchable generators, loads and energy storage to achieve feasible islanding during any potential disruptive event. In that way, the transition between grid-connected and islanded modes can be made with the minimum disruption to consumers. When isolated from the upstream grid with the aid of tie switches, MGs can operate in a self-sufficient way or can be coupled or networked with neighboring MGs, forming multi-MGs (MMGs) in order to supply critical loads (e.g., hospitals and data centers)[23] by sharing power resources[51,52]. Defensive islanding aims to the formation of efficient, self-adequate MGs or to the isolation of the vulnerable areas with the minimum load curtailment to avoid cascading events.

The main goal of these strategies is to prevent total or partial blackouts and minimize or even eliminate load curtailments by optimally scheduling and dispatching DERs, including storage and by prioritizing the supply of critical loads.

Due to the inability to predict the exact time, area, and duration that a natural disaster will hit and last, resilience preventive and emergency operational strategies are often scheduled in a stochastic or probabilistic way, in order to model uncertainty[53]. Besides the time, progress and duration of the event, RES' generation and the estimated damage to power system infrastructure can be modeled using a stochastic approach. The variability of energy market prices can be also considered[53].

There is increasing interest in preventive scheduling and emergency strategies using MGs, focusing mostly on MG islanding approaches[54–71].

2.3 Resilience-oriented operational measures for restoration

In case of power system complete or partial blackouts, MGs can contribute to the power system restoration process as an effective black-start resource[72]. Restoration must ensure that consumers who have experienced power interruptions are re-connected fast, while system component damages are repaired. Then, the system should return to its normal operating conditions. Efficient management of repair crews plays a vital role in the restorative phase, in order to reduce restoration time.

Several resilience-based MG load restoration and self-healing techniques have been developed in the literature during the last decade[73–85].

After a disastrous event and the power system infrastructure restoration to a resilient state, conclusions about the system's performance and the impact of the event should be extracted, in order for the system to better withstand any major future disruption. Thus, it is important for the power system to be adaptive and reflective to any potential threat, as a key feature of a resilient infrastructure[21].

Table 1 classifies the literature on planning and operational measures for power system resilience enhancement using MGs.

3 Microgrid-based resilience enhancement methods

This section aims to describe in detail the various resilience methods proposed and associate them to the power system level they are applied to, i.e., transmission system, distribution system or individual MG resilience enhancement, as presented in Figure 2 and Table 2. Furthermore, the techniques employed to model potential uncertainties (e.g., outages caused by extreme events, RES generation stochasticity, loads demand, real-time market prices, etc.) are discussed and grouped in deterministic, stochastic and robust approaches. Table 3 summarizes the related literature classification, as described above.

The section retains the classification of the methods according to the resilience states of the trapezoid, as described in Section 2.

3.1 Long-term resilient system planning using microgrids

A number of studies have been published dealing with resilience-oriented power system optimal planning using MGs. Papers concern transmission systems[44,45] and distribution systems[40,41,46–47], while the frameworks described in refs. [42,43,49] are associated with system planning using individual resilient MGs.

The objective functions for resilient system planning usually address the minimization of investment and operating costs under budget constraints for hardening and DERs placement[40,41,48]. They can also include optimal placement and sizing of MG to ensure cost minimization of load curtailments against potential extreme events[44,49]. Some frameworks aim at generation cost minimization

Table 1 Microgrids planning and operational mesures

Categories	Sub-categories	Related work
MG resilient planning	—	Refs. [40–49]
MG operational measures for resilience enhancement	Preventive MG scheduling and emergency measures	Refs. [54–71]
	Restoration techniques	Refs. [73–85]

Table 2 Classification of methods according to the system level they are applied to

Categories	System level		
	Transmission system	*Distribution system*	*Individual microgrids*
MG-based resilient planning	Refs. [44,45]	Refs. [40,41,46–48]	Refs. [42,43,49]
Preventive MG scheduling and emergency measures	Ref. [70]	Refs. [65,69]	Refs. [54–64,66–68,71]
Restoration techniques	—	Refs. [75,77–82,84,85]	Refs. [73,74,76,83]

Table 3 Classification of methods according to modelling uncertainty

Categories	Method		
	Deterministic	*Stochastic*	*Robust*
MG-based resilient planning	Refs. [42,43,45,49]	Refs. [41,44,48]	Refs. [40,46,47]
Preventive MG scheduling and emergency measures	Refs. [64,66,67,69]	Refs. [54,57,58,63,65,70,71]	Refs. [55,56,59–62, 68]
Restoration techniques	Refs. [73,74,76–79,82–85]	Refs. [75,81]	Ref. [80]

and voltage regulation[45], optimizing capacity of dispatchable DERs[46,47] and include hierarchical control strategies for MGs[42,43].

There is a variety of methods used to capture the uncertainties of diverse parameters (e.g., contingencies due to extreme weather, RES power outputs, load demand, etc.). Deterministic frameworks are used in refs. [42,43,45,49], while robust methods are employed in refs. [40,46,47] and stochastic formulations in refs. [44,48]. A hybrid stochastic method with a deterministic casual structure is developed in ref. [41]. In the following, details about the various methods are provided.

Modeling of failure events commonly uses the power lines N–K contingency criterion (worst-case scenario)[40], fragility models for poles and power lines[41], engineering assumptions about islanding and resynchronization periods[42,43,49] and component outages[45,47,48] and power lines and generation units contingencies obtained from probability distribution functions[44].

A non-cooperative game-theoretic framework for system planning using MGs is proposed in ref. [45]. Two decentralized update schemes for MGs in a resilient transmission system are presented. The whole resilience-based framework incorporates economic factors, taking into account the stability and efficiency of MGs. The application of this study uses a deterministic method with two failure models, a potential generator breakdown and an open-circuit of a transmission line. In ref. [44], a mixed-integer linear programming (MILP) optimization problem about MG placement is presented. In order to maximize transmission system resilience, the proposed methodology determines the optimal size and placement of MGs considering multiple component outages and a limited investment budget. A stochastic approach is used to model potential hurricane contingency scenarios.

In ref. [40], a MG planning approach for distribution system resilience enhancement against hurricanes is presented. A two-stage robust optimization method is employed. The first stage determines the lines to be hardened and the DER placement, while the second stage determines load shedding under the worst-case scenario taking into account the network planning decisions of the first stage. In order to capture the uncertainty of a natural disaster, a multi-stage and multi-zone based uncertainty set is used, as an extension of the traditional N–K contingency criterion. In this way, the hardening measures and DER allocation to enable the formation of MGs in the event of multiple line damages are determined. The strategy proposed in ref. [41] consists of three resilient-oriented MG design measures for power distribution systems against wind-induced climatic hazards. The measures include line hardening, installation of backup DGs and the addition of automatic switches. In order to model the spatio-temporal correlations of uncertainties, a mixed-integer two-stage hybrid stochastic method with a deterministic casual structure is developed. This study aims at minimizing the MG design investment cost in the first stage and the distribution system expected operational and restoration cost in the second stage, by sectionalizing the distribution system into self-supported MGs. A mixed-integer second order conic optimization program (MISOCP) is developed in ref. [48]. This study utilizes a two-stage stochastic method that optimizes MG investments in energy storage in the first stage and re-routes mobile energy storage to form dynamic MGs, in case of emergency, in the second stage, using the progressive hedging (PH) algorithm. This framework employs a mixture of system planning and operational measures in order to enhance distribution system resilience. In ref. [46], an optimal planning MILP scheme for distribution networks is proposed, determining generation units' capacity and MG placement to potentially perform both partial and full restoration in a resilient manner. A robust optimization method is used. The multi-stage exhaustive search algorithm is based on worst-case scenario analysis under several severe fault scenarios. In ref. [47], a multi-objective MILP approach of MG planning is proposed, in combination with switching operations. The purpose of this robust optimization scheme is to maximize the resiliency of distribution networks against natural disaster, in terms of service to the critical loads, and minimize the necessary dispatchable power generation capacity of MGs. A variety of contingency scenarios is taken into account. At the same time, an analysis of variance exhaustive search algorithm is used to evaluate the accuracy of the extracted results.

In ref. [43], a software-defined networking (SDN) based communication architecture and control strategy to enhance MG resilience is developed and evaluated via a hardware-in-the-loop (HIL) environment based on a campus MG at the University of Connecticut. The aim of ref. [49] is to quantify the resilience enhancement benefits provided by installing a MG in a hospital. In the proposed MILP model, a deterministic method is utilized. MG's component sizing is optimized by considering both economic profitability and resilience capacity. In ref. [42], a hierarchical control strategy is proposed to enhance the economic and resilient operation of the Illinois Institute of Technology DC MG and the results are compared with the AC model. Also, MG unintentional islanding and loads restoration processes are performed through tertiary control.

3.2 Resilience-based preventive and emergency measures using microgrids

In this section, MG-based preventive and emergency operational strategies are grouped according to the system level at which they contribute to improving resilience, i.e., transmission systems, distribution systems or individual MGs. Ref. [70] refers to transmission systems, refs. [65,69] correspond to distribution systems, while the frameworks in refs. [54–64,66–68,71] are related to resilient MG operation.

The objective functions for MG-oriented preventive and emergency resilience enhancement usually consider maximization of revenues from selling power to its customers and the upstream network and minimization of operational costs. These include costs for power and heat production, load curtailment, units start-up and shut-down costs, storage units degradation cost, power purchasing from the upstream grid, spinning reserves, etc.[54,55,57–61] Some frameworks focus on load curtailments minimization[56,63] and other models include optimal trading of power surplus among networked MGs[64,68,69]. Some of the aforementioned objective functions comprise tri-level structures to determine the worst realization of uncertainties[55,59] and some others use probabilities to capture a variety of possible scenarios[54,57,58].

Regarding uncertainties, the studies in refs. [54,57,58,63,65,70,71] utilize stochastic models, robust methods in refs. [55,56,59–62,68] and deterministic frameworks in refs. [64,66,67,69] are employed.

The techniques commonly used to model failure events are based on the determination of islanding and resynchronization time periods obtained from probability distribution functions of various scenarios[54,57,58]. They use the budget-of-uncertainty-based definition of worst-case scenario[55] or dynamic boundaries[61]. Other techniques model failure events considering outage probabilities of vulnerable lines and poles obtained from fragility curves (e.g., due to windstorms in ref. [56]), tri-level objective functions that derive the worst-case scenario contingencies using duality theory[59,60,62,68] and engineering assumptions about islanding time and duration and component outages[64,69].

In ref. [70], a MG-based mixed-integer non-linear optimization (MINLP) emergency model is analyzed. The purpose of this study is to enhance the resilience of a transmission system that is exposed to a progressing wildfire. This study proposes a two-stage stochastic optimization structure. The first stage decides the number of power reserves that need to be purchased by the utility, while the second stage determines DG units dispatch, MG islanding and load shedding for various scenarios. In order to model the intensity of the wildfire as an uncertain parameter, 100 different scenarios are generated, using probabilities.

In ref. [65], a hierarchical outage management control scheme for distribution system resilience enhancement is proposed. In order to achieve resilience enhancement, this MILP optimization scheme uses MMGs. A stochastic method is utilized. In the first stage, the MG schedules are revised using a model predictive control-based algorithm and in the second stage, the distribution system operator (DSO) coordinates the possible power transfers among the MGs and utilizes the unused capacities of their resources for feeding the unserved loads in stage one. Two-stage MMGs scheduling for distribution systems resilience enhancement, using a hierarchical energy management framework is proposed in ref. [69]. The structure of this study comprises a MILP formulation, where RES production and load demand are considered accurately predicted. In the first stage, each MG reschedules its available resources to minimize load curtailments and operational costs using the rolling horizon optimization and in the second stage, a consensus algorithm is applied for MG distributed communication to coordinate and determine the power exchange plan, in order for MGs with surplus power capacities to export power to support MGs with load curtailment.

A linear framework for resilient MG scheduling is developed in ref. [54]. A two-stage stochastic method is employed in order to capture the uncertainties of wind production, electric vehicle behavior and real-time market prices. The first stage determines the optimal scheduling of resilient MGs while the second stage determines the real-time operation of MGs. The goal of ref. [63] is to present a MG-based resilient preventive scheduling against extreme floods. This MILP framework employs a stochastic method, using fragility curves of outdoor substations and underground cables to calculate the component failure probabilities under different rainfall intensities. Worst-case scenario analysis is considered to determine MG status. In ref. [57], a risk-constrained framework for joint energy and reserve scheduling of a resilient MG is presented. A stochastic model is employed considering demand side management, RES output power, load demand, electricity prices and contingency-based uncertainties. In ref. [71], a statistical framework to quantify the resilience of both military and hybrid MGs is analyzed. Its purpose is to express the probability of these MGs meeting critical load requirements during a potential islanding event. Probabilities are evaluated by using Markov chains that describe MG survivability, composing a stochastic optimization model. In ref. [58], a resilience-economic MG scheduling is developed. This study uses a multi-objective MILP scheme and a stochastic method is employed to model the uncertainties of real-time energy prices, wind resource generation, as well as event time and duration. In ref. [62], a resilience-oriented MILP optimal MG scheduling approach is presented. This study uses a robust optimization method considering two worst-case analysis scenarios when modeling load and power generation forecast. The worst-case solution is obtained when the non-dispatchable generation is at its lower uncertainty bound and the load is at its upper uncertainty bound, because of the high mismatch. The main grid supply interruption time and duration uncertainties were captured via islanding scenarios. The feasibility of resilient operation is ensured via three actions, which respectively revise the schedule of controllable units, energy storage and loads. A resilient MG scheduling model is proposed in ref. [59]. This two-stage optimization procedure employs a robust method to take into account the uncertainty of both RES production and load demand and can support possible islanding incidents. In the first stage, the DGs and ESSs are prepared for potential disruptions by maintaining certain amounts of flexibility which can be deployed in the second stage, when the utility grid is interrupted, to supply the local demand. The pre-disturbance resilient MG scheduling framework of ref. [55] aims to minimize the consequences of islanding events, considering uncertainties and budget of uncertainty parameters. An adaptive two-stage robust MILP formulation is used. In the first stage, the commitment status of DGs as well as the MG bids and offers in the day-ahead market are determined. The second stage concerns the dispatch of DGs, storage units, elastic loads and the MG bids and offers in the real-time market. A resilient MG preventive management framework against extreme windstorms is introduced in ref. [56]. In order to achieve that, the proposed linear programming (LP) approach exploits network reconfiguration, power re-dispatch, conservation voltage regulation, optimal parameter settings of droop-controlled units, demand-side resources and backup generation capacity. A robust optimization method is utilized to capture the wind-induced contingency uncertainties. In ref. [60], a resilience-based MG scheduling method is developed to potentially ensure successful islanding. A robust optimization model is employed to generate multiple scenarios of renewable energy generation (wind and PV power) and load demand. In ref. [61], a resilient MG scheduling is presented, taking into account the system frequency dynamics aiming to prevent frequency instability due to the high power electronics penetration under a potential unintentional islanding event. To achieve this, synthetic inertia control is applied in order to regulate the active power output of the Inverter-Based Generators to support the post-islanding frequency evaluation. A MISOCP is formulated, employing a robust method considering the stochastic uncertainty associated with RES and load. In ref. [68], a resilience-oriented emergency strategy for hybrid networked MGs (NMGs) is presented. More specifically, this study considers NMGs feasible for the islanding and survivability of critical loads during the emergency period. A robust optimization method is employed to model RES generation and power demand. An incremental cost consensus algorithm is used for the optimal allocation of surplus power among the connected MGs that have unserved loads. An energy management strategy for day-ahead resilient scheduling of NMGs is proposed in ref. [64]. In this nested energy management system approach, a privacy-preserving mechanism for information sharing within local MGs is proposed. This study constitutes a MILP structure utilizing deterministic methods for both grid-connected and islanded modes. The performance of the proposed strategy is also assessed for hybrid AC/DC MGs. In ref. [66], a methodology for MMGs energy carrier networks resilience reinforcement is analyzed. A mixed-integer bi-level programming (MIBLP) framework, utilizing a deterministic method, is developed to ensure the resilient operation of coordinated electricity and natural gas infrastructures, by identifying their vulnerable and critical components. A resilience-based MG neighborhood forming optimization technique is described in ref. [67] for distributed monitoring, dynamic re-configuration and control of DC distribution topology in a service-oriented architecture. A deterministic method is utilized.

3.3 Resilience-based microgrids restoration strategies

As in the previous sections, MG-based resilient restoration is grouped according to the system level. However, none of the related work corresponds to the transmission system. The frameworks of refs. [75,77–82,84,85] refer to distribution systems and refs. [73,74,76,83] are related to resilient MGs restoration.

The objective functions for MG-oriented resilient load restoration usually maximize the prioritized load pick-up and the system performance considering minimization of operational cost and overall load restoration time[74,77,79,82,83]. In this context, the objective function of ref. [80] also utilizes duality theory to find the worst-case scenario of DER output. Other objective functions optimally decide whether feeder root nodes or mobile emergency generators should be used to restore critical loads[75]. Other frameworks aim at maximizing the unused capacity of networked MGs and at optimizing power exchanges among them to achieve faster and more efficient overall load restoration[76]. Other methods address optimal MGs scales for lower exposure to potential risks and determine optimal interconnections among adjacent MGs[73,81].

Different methods are commonly utilized in order to model the various uncertainties of these procedures. Mostly deterministic frameworks are used, specifically in refs. [73,74,76–79,82–85], while stochastic methods are employed in ref.s [75,81] and a robust model is utilized in ref. [80].

Most failure events are modeled via engineering assumptions concerning power line outages[73,74,76–79], while other models use probability distribution functions to describe a variety of outage scenarios[75].

In ref. [80], a MG scheduling method based on robust model predictive control is developed for the resilience enhancement of distribution networks. The main contribution of this two-stage scheduling strategy is to sectionalize the outage distribution network into MGs and optimally schedule its DERs (first stage), in order to use robust model predictive control for quick load restoration (second stage), considering the uncertainty of RES power output. In ref. [77], a resilient-based distribution system critical load restoration strategy by forming MMGs is presented. This deterministic MILP multi-agent coordination scheme aims at maximizing the critical loads to be picked up while satisfying the self-adequacy of the MGs formation problem, after a disastrous event. A strategy for improving the resilience of grid-edge distribution power systems is analyzed in ref. [78]. The reported deterministic strategy aims to coordinate the use of local resources, in islanding conditions, as well as temporarily form clusters of MGs or cooperatives of smart homes in order to restore the system to its normal operation. A resilience-based methodology that uses MGs to restore critical loads on distribution feeders considering the dynamic performance of DGs during the restoration process is developed in ref. [79]. This deterministic framework incorporates the stability of MGs, limits on frequency deviation and transient voltage and current of DGs as constraints of the proposed linear integer programming (LIP) problem. In ref. [82] NMGs-based MILP method for service restoration in resilient power distribution networks is developed. Power outages and RES production is modeled in a deterministic manner. This framework aims at both maximizing the load pick up and minimizing the restoration process time. In ref. [84], a MINLP MG formation model for resilient power distribution networks is developed. This study utilizes a deterministic formulation and considers power loss and voltage constraints in the power balance and operation feasibility. In ref. [85], a sequential service restoration framework is developed to generate resilient restoration solutions for distribution systems and MGs in the event of large-scale power outages. This deterministic MILP optimization methodology contains a sequence of control actions to coordinate switches, dispatchable DGs and switchable loads in order to form self-adequate MMGs. The rolling-horizon method is applied to reduce the extensive computation complexity for large-scale systems. The study of ref. [75] introduces a two-stage stochastic optimization approach of dispatching mobile emergency generators in distribution systems to restore critical loads by forming MMGs during a natural disaster. Thus, a two-stage dispatch framework consisting of -prior to a natural disaster- pre-positioning (first stage) and -after the disaster strikes- real-time allocation (second stage) of mobile emergency generators is proposed and their transportation delay issue is considered via the vehicle routing problem. The objective of the problem is the minimization of the expected outage duration of loads considering their priorities and demand sizes. In ref. [81], a MILP structure with a NMGs-aided coordination approach for service restoration in resilient distribution systems is presented. A stochastic optimization method is employed, considering the uncertainty of the customer load demand and DG outputs and, as a result, these parameters are modeled in a scenario-based form. In this study, a centralized (where all MGs are controlled by the distribution system operator) and a decentralized (where the distribution system and MGs are managed by different entities) approach are developed and compared in order to facilitate service restoration.

In ref. [73], a resilient MMG-based service restoration method is proposed, considering additional financial and security risks due to potential subsequent outages to local utility customers. The formation of MMGs and load switching sequence steps, along with optimally positioned mobile emergency resources, ensure the system's dynamic performance in the restoration process. A deterministic method is employed to model the line outages. In ref. [74], an analysis of the control and management system for a resilient post-hurricane integrated recovery framework is presented. This strategy uses resilient NMGs to decrease blackouts to a minimum time. To produce optimal routes and avoid out-of-service roads, this study uses Dijkstra's algorithm. In ref. [76], a two-stage resilience-oriented nested restoration decision system for power distribution systems MGs is proposed. This deterministic framework's purpose is to minimize the unused capacity of DGs for service restoration due to contingencies provoked during the islanding stage, by facilitating coordination between neighboring MGs. The first stage refers to the pre-event scenario, which determines a solution for networked MG distributed generation as the initial setting. The second stage finds additional re-distribution requirements, based on respective MG's deficiency, using a solution index matrix. A resilience-based load restoration strategy is proposed in ref. [83]. This MISOCP optimization model aims to control and coordinate the topology reconfiguration and resilient MG formation in distribution power systems. A deterministic method is utilized in order to model the outages. The MG forming model is formulated considering master-slave DG operation where the presence of a singular master DG in each island guarantees self-supply.

4 Conclusions

This paper reviews state-of-the-art strategies that use MGs in order to enhance power systems resilience at all states that a system might reside in the event of an external threat. These include MG-based resilient system planning, MG-based resilience-oriented preventive scheduling and emergency measures and MG-based resilient restoration. A classification of the related publications based on their association to the transmission system, distribution system or individual MG resilience reinforcement is presented. The way of treating uncertainties is also analyzed.

The authors have identified the following gaps and challenges that in their opinion require further research:

- Natural disasters can cause huge physical and economic damages to power systems. The long-term financial costs of natural disasters should be taken into account in the MG resilience planning to determine the most cost-effective investment.
- Research on the contribution of MGs against sequential and different extreme events presents important challenges. Multi-event-oriented frameworks should ensure that the power system responds adequately even to diverse disastrous events that require different measures, e.g., wildfires and floods. A typical example of conflicting measures is network undergrounding.
- The coordination of transmission, distribution systems and MGs will help better understand a wider range of features that affect the resilience performance of a power system. Such a holistic approach will produce more efficient resilience enhancement strategies, in a coordinated manner, for the whole power system.

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The authors have no competing interests to declare that are relevant to the content of this article.

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