

TOPICAL REVIEW

Microgrids and Resilience: A Review

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ABSTRACT The occurrence of large-scale disturbances is increasing at an alarming rate throughout the world. As a consequence of this trend, a primary concern of today's power system is to enhance its resilience against low-probability, high-impact events. In this regard, microgrids, as the smart grid's building blocks, offer promising approaches toward achieving higher levels of distribution system resilience by accommodating and integrating various distributed energy resources. Accordingly, microgrid-based techniques have been the focus of a growing body of research seeking a more resilient power system. These methods mainly rely on the stand-alone operation of microgrids to supply loads locally in case of extreme events. The objective of this paper is to present an updated comprehensive review of the literature on two main categories of microgrid-based resilience enhancement approaches in distribution systems: 1) optimal microgrid formation and 2) optimal microgrid scheduling and energy management. Distinctive from other review papers, this article systematically surveys the research studies under multiple well-sectionalized features, such as various technologies, techniques, models, constraints, and concepts for each of the above two categories. These features include but are not limited to networked microgrids, demand response programs and electric vehicles scheduling, multi-energy microgrids, dynamic optimization schemes, control schemes, communication resilience, hybrid microgrids, and mobile energy resources. Additionally, a comprehensive introduction to resilience definitions and assessment methods, microgrid components, architectures, and control schemes, as well as, sources of uncertainty is provided.

INDEX TERMS Distribution system resilience, microgrid, microgrid resilience, microgrid-based resilience solution, power system resilience, resilience, resiliency.

I. INTRODUCTION

Hardly does a week go by without another report of natural hazards throughout the world appearing in the media. As shown in Fig. 1 [1], there has been a marked rise in natural disasters since the mid-twentieth century, some of which have resulted in a heavy financial loss. Although there has been a slight drop in the number of natural disasters in recent years, the evidence is accumulating that more catastrophic events tend to happen. According to National Centers for Environmental Information [2], from 1980 to 2009, the annual average number of weather-related disasters in the U.S. with losses exceeding \$1 billion for three consecutive decades has been 3.1, 5.5, and 6.7, respectively, while this number for the time range of 2010-2021 has been 14.2. Even more alarming for researchers is mounting evidence that this

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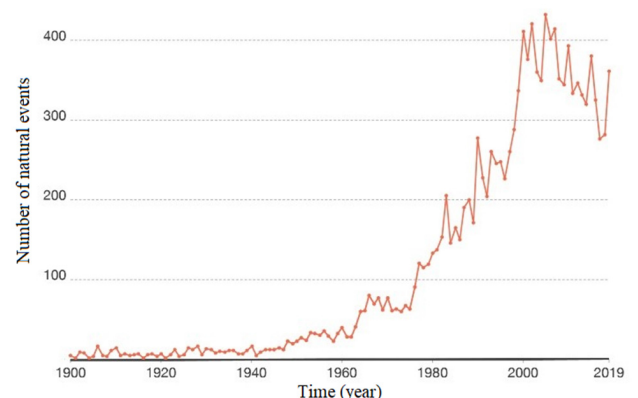


FIGURE 1. Number of all recorded natural disaster events, 1900 to 2019.

upward trend in the severity and occurrence rate of natural disasters—particularly those related to heat—is driven by human-caused climate change [3].

In this regard, the increasing frequency and intensity of extreme events is a matter of grave concern to energy infrastructure; particularly, the electric power system is inherently susceptible to damages and outages, with significant consequential losses. Natural hazards, viz., meteorological (e.g., extreme temperatures, tropical cyclones, and severe storms), geological (e.g., earthquakes and volcanic eruptions), hydrological (e.g., floods, droughts, and tsunamis), and biological (e.g., epidemics and pandemics) phenomena [4], inflict extensive damage and loss on electric power sector each and every year. Table 1 displays the most extensive blackouts in U.S. history with the most cumulative lost customer-hours of electricity service [5]. What stands out in the table is that, except the Northeast Blackout, which was caused by cascading failure, 9 of the ten biggest blackouts were brought about by cyclone events. Yet, even more problematic, severe weather, as the primary cause of outages and fuel supply disruptions in the U.S., is projected to deteriorate, given the fact that 8 of the ten most destructive and costliest hurricanes of all time have occurred in the last decade [6], [7]. Furthermore, in addition to natural hazards, the power system is exposed to malicious physical and cyber-attacks which may lead to power outages and even blackouts.

Having continued traditionally and successfully, single or double outage contingency ($N-1$ or $N-2$) has been the main criteria to guarantee system reliability. These criteria refer to the ability of the power system to withstand an unexpected failure/outage of a single system component or simultaneous failures/outages of two single system components. In such high-probability, low-impact contingencies, the grid components remain undamaged for the most part, and a relatively small number of customers are affected for seconds, minutes, or seldom, for some hours. Whereas catastrophic events, alarmingly, may entail multiple failures, outages, and even destructions in system components, and therefore, multiple outages contingency ($N-k$) analysis should be conducted. In such cases, the overriding concern of system operators is to sustain the operability and functionality of critical infrastructure during and after the extreme event, keep the direct and indirect losses at a minimum, and mitigate catastrophic consequences in the aftermath of the event [8]. Here is why a clear-cut distinction should be drawn between reliability and resiliency. Recent trends in extreme events and consequent losses have necessitated the study of power system resilience to gain momentum.

As regards power system resilience, the emergence and development of a broad array of smart grid technologies, architectures, and applications offer viable, intelligent solutions. Toward this end, microgrid (MG), an essential part of smart grids, could afford unprecedented opportunities. Briefly speaking, MGs are small-scale power systems connected to the distribution system (DS) at the low- or medium-voltage level, capable of integrating distributed energy resources (DERs) and being operated in stand-alone or grid-tied modes. Owing to these capabilities, MGs have shown great potential to improve system resilience. In recent years

TABLE 1. Biggest blackouts in the U.S. history.

Blackout/Cause of blackout (year)	Lost electricity service (million customer-hours)
Hurricane Maria (2017)	3,393
Hurricane Georges (1998)	1,050
Hurricane Sandy (2012)	775
Hurricane Irma (2017)	753
Hurricane Hugo (1989)	700
Hurricane Ike (2008)	683
Hurricane Katrina (2005)	681
Northeast Blackout (2003)	592
Hurricane Wilma (2005)	515
Hurricane Irene (2011)	483

there has been an increasing amount of literature emphasizing the optimal use of DERs and MGs in improving power system resilience. Accordingly, this study aims to contribute to this growing research field by providing a systematic and updated review on MG-based resilience enhancement methods in power systems. This paper will survey the research conducted in this area under two main categories:

1. Resilience-oriented MG formation and resource allocation within the DS
2. Resilience-oriented MG optimal scheduling and energy management

Furthermore, distinctive from other review papers in this field, each of these two sections is further divided by important features used in the literature. These subsections cover different technologies, practices, techniques, models, constraints, methods, and concepts used in the existing, and particularly, most recent literature.

The remainder of this paper is organized as follows. Section II contextualizes the preliminaries to conduct the review on MG-based resilience enhancement methods. An outline of resilience enhancement methods in the power system is presented in Section III. Section IV reviews the literature on resilience-focused optimal MG formation and resource allocation within the DSs. Section V attempts to provide a literature review in the resilience-oriented MG scheduling and energy management field. The future research directions are presented in Section VI while conclusions are drawn in Section VII.

II. PRELIMINARIES

The following sub-sections contextualize the background information on resilience and MG.

A. RESILIENCE

1) RESILIENCE DEFINITION

Having discussed the recent trend in natural hazard occurrence and consequent losses, it is necessary to be explicit about precisely what is meant by resilience. Although several definitions have been proposed in the literature, a generally

accepted one is lacking. Resilience is an umbrella term covering a broad range of factors. It may be defined as the ability to prepare sufficiently for and withstand robustly low-probability, high-impact events to effectively mitigate their damaging impact and/or reduce the duration of the disruption, which encompasses the potential to absorb, adapt to, capture uncertainties of, and quick recovery from such events.

Panteli et al. [9] suggest two broad categories of resilience: 1) infrastructure resilience and 2) operational resilience. To delineate, the former is defined mainly as the strength of the physical layer of the power system to resist and be less susceptible to damage from major disruptions. The latter refers to operational continuity, i.e., uninterrupted supply or generation availability, despite major events. The dashed box in Fig. 2 displays the characteristics required for a resilient power system in chronological order under extreme events described in the following subsection.

Since roughly 90% of blackouts in the U.S. are initiated from failures in the DS, power system resilience is regarded as equivalent to DS resilience [10]. Therefore, this paper uses the terms “power system resilience” and “DS resilience” interchangeably. The following part of this paper moves on to discuss the quantitative view and metrics of DS resilience.

2) RESILIENCE ASSESSMENT

To effectively develop system resilience—either to guide enhancement efforts or to assess their effectiveness [10]—it is of paramount importance to understand the factors contributing to resilience and quantify its level accordingly. Resilience corresponds to a quantifiable measure of system performance that embraces operation and infrastructure resilience factors. The relevant performance indicator for operation resiliency can be the number of customers connected to the grid, the percentage of supplied total or critical loads, maintaining frequency and voltage stability [11], available generation

capacity, and the like. In contrast, the portion of re-established or repaired system components which have become nonfunctional [9] may serve as an index of infrastructure-related performance. Fig. 2 illustrates a typical curve for system performance as a function of time, also called the resiliency curve, during the time that an extreme event unfolds.

Since prior to most extreme events, some levels of predictability are within reach, and proactive/preventive measures are taken, once the event alert is declared in t_e , the system is prepared to absorb or withstand the initial shock to some degree, thereby maintaining the pre-disturbance performance level (Q_0) and postponing the realization of event impact until t_1 . However, the event intensity and the system’s infrastructural resilience are other key determinants of this capability at the event onset [11].

As the event progresses or escalates, system performance witnesses a sharp drop in t_1 . Meanwhile, during this period, proper operational corrective actions are implemented immediately to mitigate the degradation level and maintain the system performance at the best possible level during the degraded state ($t_2 - t_3$). However, it would be the lowest system performance point, i.e., Q_{min} , in this period. During this time, the system is getting prepared for the operational and infrastructural restoration at t_3 ; however, the time required to initiate these recovery efforts differs from each other. First, the post-disturbance operational measures enhance the system performance to Q' at t_4 . Depending on the effectiveness of these actions and operational resiliency displayed by the system [12], it could be equal to or lower than the pre-disturbance system performance level. Then, system performance is maintained until the infrastructural recovery efforts begin at t_5 . As can be witnessed in most real cases, the infrastructural recovery starts later and takes longer than operation-oriented resilience restoration. For instance, the end-users might be fully resupplied before the full restoration

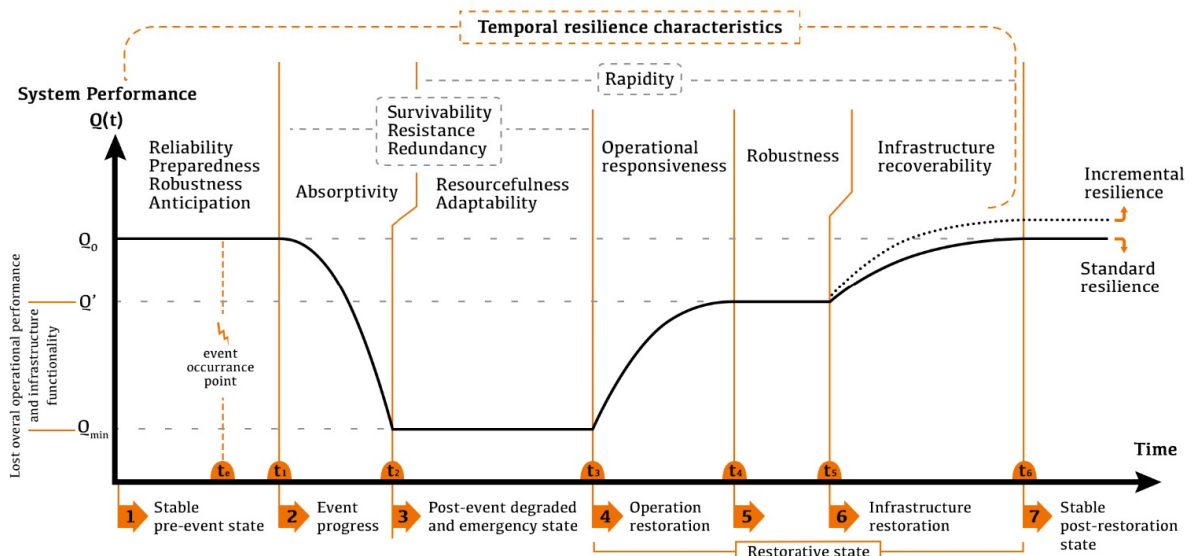


FIGURE 2. Resilience curve and temporal requirements of a resilient power system.

of damaged components [9]. Depending on the repair efficiency, the functionality of interconnected infrastructures, as well as, event intensity and duration [11], the physical restoration processes vary in duration, the end time of which is t_6 . At this time, the system is fully restored, and the system performance level equates to that of the pre-disturbance state; however, since some components are replaced by brand-new equivalents or even modernized or upgraded into more robust ones after completion of the reconstruction process, the infrastructural performance of the system might be higher than Q_0 [13].

B. MICROGRID

The concept of MG was first introduced by Lasseter and Paigi [14] as a group of micro-sources and loads operating as a single controllable system. Fig. 3 depicts the general structure of a MG. The U.S. Department of Energy defines a MG as “a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode [15].”

Unlike traditional centralized grids, MG, as its definition indicates, is mainly designed to accommodate and integrate DERs, enabling it to supply its loads in a local manner, which does not necessitate expensive transmission facilities. A MG can disconnect itself from the main grid to operate in islanded mode, which guarantees its independent operation, even in case of disconnection from the upstream grid. By and large, it is not too much to say that with the increased integration of DERs and intelligent operation measures, MGs can be regarded as the cornerstone of smart grids. The following subsections will provide further details and categorizations of the MG’s components, architectures, and operation.

1) MICROGRID COMPONENTS

At the outset, MGs were introduced to integrate the various DERs, including dispatchable distributed generators (DGs), renewable energy sources (RESs), and energy storage systems (ESSs), as well as flexible loads. MGs are further established as alternatives to centralized generation and bulk transmission in power system operation and planning [16]. The main MG components are as follows.

a: GENERATION

Electric power generators in a MG can be categorized into dispatchable and non-dispatchable units. Dispatchable units (e.g., diesel generators, fuel cells, and microturbines) refer to resources that can be controlled in a centralized manner regarding electricity market demand. MG operators can commit and dispatch these units subject to technical constraints like generation capacity, fuel availability, ramping, minimum on/off time, and emission limits [17]. The other way around, non-dispatchable units, generally comprising RESs, such as wind turbines (WTs) and photovoltaic (PV) panels, cannot be controlled by operators due to intermittency

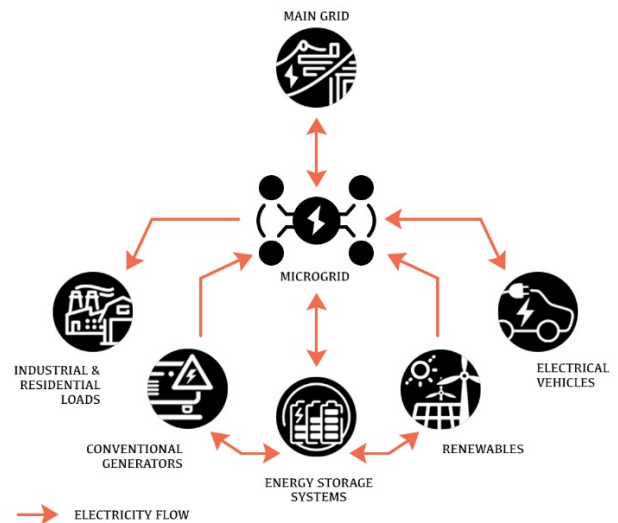


FIGURE 3. Microgrid general structure.

and volatility of generated power. This variable nature stems from the uncertainty in the meteorological forecasts, which determine the input source of such units, e.g., wind speed and solar irradiance. However, the significant advantages of these generators are that they are zero-fuel-cost and emission-free.

b: CONSUMPTION

Generally, MG energy consumption includes electricity, heat, and cooling loads. Electrical consumption within a MG can be classified into fixed or adjustable loads. Fixed ones, mainly as the most critical loads such as hospitals, police stations, and data centers, cannot be altered and must be met under normal and emergency operation circumstances. Therefore, this type of load cannot be scheduled in the demand response (DR) program. On the contrary, for the adjustable loads, the power consumption can be reduced by MG operators based on market price and required control actions. Adjustable loads can be either curtailable or shiftable; these loads depending on their supply priority, i.e., non-supply or delayed supply cost, can be shed or deferred, respectively, responding to monetary incentives or islanding requirements [17], [18], [19], [20].

c: STORAGE

To address the variable generation of non-dispatchable units, they are coupled with ESSs to compensate for the generated power intermittency and volatility and ensure the MG generation adequacy. These systems also can provide such ancillary services as frequency regulation and voltage control support, load following, and peak shaving. Additionally, ESSs have the potential to improve power quality, stability, and reliability. Generally, electric ESSs (other than thermal ESSs) are of three kinds: 1) electrochemical systems (batteries and flow batteries (regenerative fuel cells)), 2) potential energy storage (pumped-hydro and compressed-air storage), and 3) kinetic energy storage systems (flywheels) [21], [22].

Moreover, ESSs can be used to load shifting by storing energy at peak price intervals and generating it back to the MG during off-peak periods [17]. Similarly, vehicle-to-grid (V2G) technology enables plug-in electric vehicles (EVs) to communicate with the power grid to either return their stored power to the main grid or increase/decrease their charging rate. Furthermore, ESSs are critical in supplying local loads and accommodating RESs by maintaining optimal amounts of both up- and down-spinning reserves in case of islanding events [23].

2) MICROGRID ARCHITECTURES

Regarding the type of their common bus, or, equivalently, the characteristics of generation and consumption, MGs can be classified into AC, DC, and hybrid AC/DC configurations.

a: AC MGs

The principal advantage of AC MGs, as the most used configuration, is their direct connection to the existing AC main power grid. Therefore, they have a comparatively higher degree of flexibility and reliability by exploiting the already available standards, protection schemes, and other applications. Examples of dispatchable generation units of AC MGs are microturbines, gas engines, and Stirling engines [24].

b: DC MGs

Recently, there has been an upward trend in DC MG installation, mainly due to direct accommodation of the high-penetration DC loads (e.g., EVs, appliances, DC lamps, DC air conditioners, and computers) and DERs (e.g., PV panels, fuel cells, and batteries). These factors have led to a significant reduction in power conversion loss; depending on the number of back-and-forth conversions (rectifications and inversions), these losses might account for 5% to 15% of power generation [21]. Furthermore, these MGs enjoy relatively more uncomplicated operation. A DC MG has nothing to do with reactive power and frequency control; therefore, it is never confronted by circulating reactive currents and harmonic distortions issues [25]. Also, the synchronization of these MGs with the main AC grid solely requires voltage magnitude adjustments, while for AC MGs, voltage magnitude, frequency, and phase shift between two ends of PCCs must be regulated [10], [26].

Since DC MGs require short transmission distances and have more efficient ESSs, they are relatively more energy efficient when implemented with various DGs. However, despite lower operation cost and smaller size, the main disadvantage of DC MGs is their high capital cost [22].

c: HYBRID AC/DC MGs

A hybrid AC/DC MG, as depicted in Fig. 4, is composed of AC and DC DGs, ESSs, and loads by connecting the AC and DC MGs with an interlinking converter. By well exploiting the technical advantages of both AC and DC MGs, hybrid MGs are regarded as a promising approach to design future MGs. Such MGs facilitate the integration of various DERs,

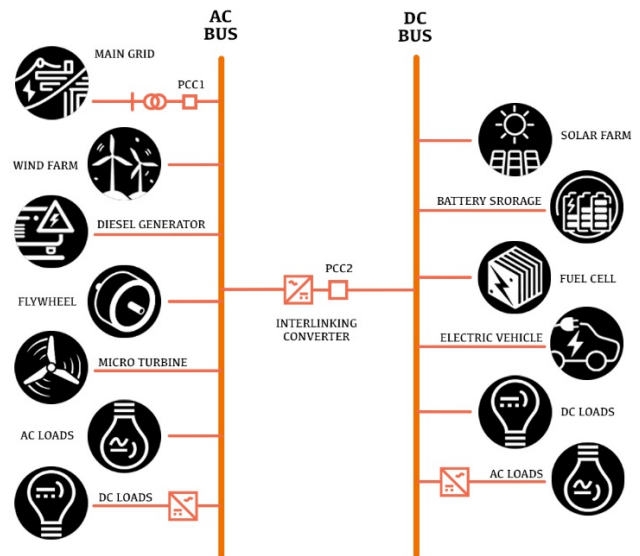


FIGURE 4. Hybrid AC/DC MG structure.

decrease the number of conversion stages, and, more importantly, reduce power loss and total costs while enhancing reliability. In these MGs, WTs and PV panels are the RESs of AC and DC MGs, respectively, while the EVs are connected to DC MG [22], [24].

3) NETWORKED MICROGRIDS

Grouping and synchronizing multiple MGs is the further application and development of the concept of MG [27], which affords numerous opportunities for a reliable and resilient power system. The islanded, self-governed MGs that are geographically close to each other have the capability of networking and forming a single entity as aggregated islands from the main grid perspective [28]. These interconnected MGs are referred to as networked MGs (NMGs). The primary goal of networking MGs is to construct a structure through which they can back each other with local generation capacities in case of contingencies leading to power deficiency, thereby enhancing system stability, reliability, and resiliency.

Commonly, the DS operator is responsible for the operation of MGs, supervises their interconnection, and determines the optimal power exchange by collecting and integrating pertinent information [10]. However, some decentralized approaches have also been adopted [29]. Either way, there must be a reliable cyber network for proper communication and control.

4) MICROGRID ENERGY MANAGEMENT AND CONTROL

The optimal MG energy management and control are significant contributors to realizing its potential, especially in achieving higher levels of resilience. Optimal energy management of MGs entails minimum operation cost and maximum supply coverage while coordinating the tasks of dispatchable and non-dispatchable DGs, ESSs, adjustable loads, and remote-controlled switches under all conditions.

Therefore, different aspects of the optimization problems have to be fully considered. In this regard, accurate modeling of MG components and proper capture of the uncertainties play a significant role. The prevalent constraints to be considered are dispatchable generation capacity, distribution lines thermal limit, voltage and current limits, state of charge and capacity of batteries, as well as frequency fluctuation limits which must be controlled by at least one generation resource within each MG. However, inherent uncertainties associated with the optimal operation of MGs lead power system researchers to use stochastic models. These uncertainties and their sources are studied in the following subsection.

References [30], [31], [32], and [33] provide systematic literature reviews on MG control strategies emphasizing its technical aspects. To put it in general words, there are three approaches being adopted to operate and control MGs and DERs effectively: 1) centralized, 2) decentralized, and 3) hybrid.

a: CENTRALIZED CONTROL

In the centralized control method, a central controller such as a DS operator is responsible for collecting data (e.g., supply/demand measurement signals and bidding information), scheduling resources, and performing centralized control and operation. The block diagram of this control approach is illustrated in Fig. 5 (a). Centralized control architecture provides a more secure solution to various operational optimization problems. However, it has comparatively lower flexibility in adding new components, requires extensive computational capacity [17] and a significant amount of communication bandwidth, and is subject to single-point failures. Additionally, since the central controller has access to sensitive information, the data privacy of MGs inevitably may be intruded on [34]. To appropriately perform an optimal sequence of control actions, inter-temporal constraints must be taken into account by double- or multiple-step optimization problems [35], [36].

b: DECENTRALIZED CONTROL

In the decentralized control methods, each MG is regarded as an agent with discrete decision-making ability. In this approach, each local controller, by iterative data exchange, seeks to fulfill its objectives, subject to its constraints [17],

[37]. Fig. 5 (b) displays a schematic form of a decentralized control mechanism. An obvious advantage of decentralized control and energy management is its comparatively lower computation burden. Also, such an approach enables the plug-and-play operation, such that a new DER can readily be integrated into the MG without modifying the rest of the control architecture [22]. A notable example of decentralized control and energy management of MGs is multi-agent systems (MASs), in which interacting agents seek to control the system collectively.

c: HYBRID CONTROL

In a reasonably practical manner, hybrid control architecture combines centralized and decentralized control. Fig. 5 (c) provides the block diagram of such a control system. In MGs with fully decentralized architecture, DERs are autonomously operated via local controllers. However, due to operational interaction among them, the choice of control action or Energy Management System/Strategy (EMS) of a unit considerably depends on the actions and strategies of other ones [38], particularly under emergency conditions. Therefore, there should be a minimum level of coordination among these units. Accordingly, in a MG with a hybrid control design, DERs are grouped and controlled centrally, the outcome of which would be a local optimum point for control and operation of the group. In the outer control layer, distributed control is exercised over DER groups, concluding in a global coordination scheme among the centralized controllers, i.e., DER groups [34].

C. UNCERTAINTIES

Uncertainty in MG energy management is concerned with some factors that cannot be predicted accurately or controlled by MG operator and includes two major types [16], [39]:

1. Typical operational uncertainties derived from forecast errors, e.g., uncertainties in RESs generated power, load demand, and real-time market price
2. Contingency-based uncertainties associated with supply interruption incidents and clearance time

During unscheduled islanding events, MGs aim to supply their demand as long as possible through optimal scheduling of local resources. However, the abovementioned inherent

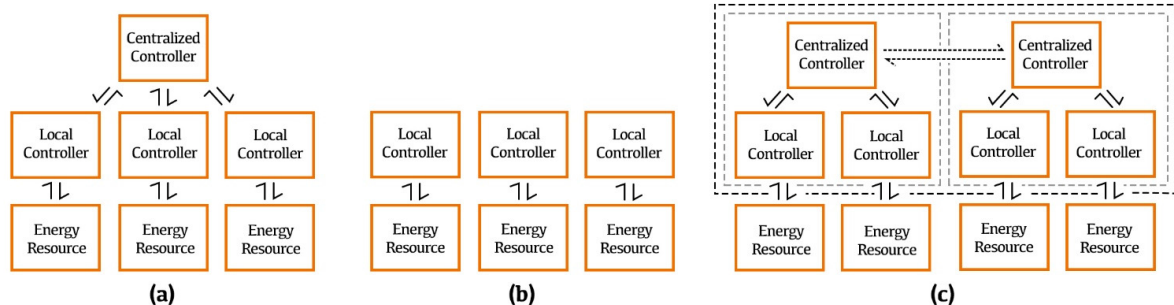


FIGURE 5. MG control architectures—(a): Centralized, (b): Decentralized, and (c): Hybrid.

uncertainties pose grave challenges along this way, such that MG ought to fulfill its varying demand with intermittent and volatile local resources for an unknown islanding duration. To cope with these uncertainties, probabilistic and statistical analyses of such uncertainties should be performed. Therefore, as will be reviewed in the following sections, numerous studies have attempted to capture these uncertainties, particularly through stochastic and robust optimization approaches.

In the case of extreme meteorological events, the time of the incident is predictable to some extent. Therefore, switching operations for islanding MGs can be done in a timely manner. However, at times, especially in rapid onset geological hazards, MG operators may have to curtail some loads in the islanding onset as an emergency strategy [24], [40]. In unscheduled islanding events, the main challenge is the unknown duration of the main grid interruption. The continuance of this disconnection depends on the time required for the main grid's repair and restoration and varies with the extent of the event's severity. To capture these uncertainties, a set of scenarios for different islanding start times and durations, based on historical data and actual situations, is defined and fed into the scheduling problem.

Uncertainty over the generation of the non-dispatchable units is mainly concerned with unalterable weather conditions like wind speed and direction, temperature, and solar irradiance, which cannot be precisely forecasted. In addition, loads naturally change dynamically, making it difficult for the MG to fulfill varying demands with an uncertain amount of generation independently. To capture this stochasticity in MG scheduling, optimization problems with different levels of robustness have been proposed. Some studies consider the worst-case scenario, which occurs when the non-dispatchable generation and load consumption of the DG are at their lowest and highest possible amounts, respectively. However, such an approach does not represent the reality of MGs and may impose overconservativeness on the scheduling solution. With an appropriate level of robustness, successful MG islanding with minimum load shedding can be guaranteed while maintaining the system's adequacy and supply security under all possible circumstances [23].

III. RESILIENCE ENHANCEMENT METHODS IN DISTRIBUTION SYSTEMS

As mentioned previously, system resilience can be broadly categorized into infrastructure and operation resilience. Along the lines of this categorization, resilience enhancement measures fall into long-term infrastructural and short-term operational methods. Infrastructural approaches are concerned with the modifications or reinforcements of the physical layer of the system to make it less susceptible to damage and facilitate system recovery in case of major power disruptions. On the other hand, operational approaches refer to mainly control-based schemes taken to accelerate system restoration and mitigate the inevitable consequences of major contingencies. The proper implementation of either of these two measures is essential for the effectiveness of

the other in case of extreme events. To put it another way, infrastructural measures may not be enough to ensure system resilience under conditions of lack of apt operation schemes. Conversely, operation-focused measures are likely to be inefficient wherein a robust and dependable infrastructure is lacking [10], [41]. What follows are further details and categorization of these methods, general procedures of traditional DS restoration, and modern MG-based resilience enhancement methods.

A. INFRASTRUCTURAL METHODS

Infrastructural methods to achieve higher levels of system resilience encompass 1) hardening and 2) planning measures. Infrastructure hardening aims at identifying and reinforcing power system components against severe disruptions and usually comprises construction programs. For instance, fortifying utility poles and overhead distribution lines, the operation of which is highly critical for the power system to confront hurricanes, blizzards, severe windstorms, and other extreme climate events. Several studies have attempted to optimize the hardening strategies of lines and other system components via vulnerability analysis ([42], [43], [44], [45], to cite a few). As another factor, proper system maintenance plays a key role in identifying aged components with a higher probability of failing in case of major contingencies to be replaced with new and more reliable ones. As regards infrastructural resilience, maintaining clearance distance between vegetation and distribution lines reduces the risk of failures during wildfires and storms [46], [47], [48], [49]. Another well-established method is to replace the overhead cables with underground ones to make the DS less susceptible to extreme weather events [50], [51]. However, the principal limitation of this procedure is its high cost; therefore, it should be optimized and implemented to a limited number of critical components.

On the other hand, planning-based infrastructural methods work toward installing new components, smart devices, and subsystems to increase the network's redundancy, automation, and flexibility. A prominent example is building supplemental transmission and distribution lines along more secure geographical routes to enhance resiliency by offering more restoration path options [52], [53]. Furthermore, this approach is exemplified by resilience-constrained optimal MG placement and installation, networking multiple MGs and increasing the generation and storage capacity leading to a useful redundancy [10], [54], [55], [56], [57], [58], [59]. Capacity expansion and hardening of transportation system can also play a key role in enhancing DS resilience [60].

B. OPERATIONAL METHODS

Generally, operation-focused methods can be classified on the basis of time into two mutually beneficial and complementary types: 1) preventive/proactive and 2) corrective/reactive measures. Preventive and proactive measures pertain to the pre-event preparation of the system to respond appropriately to unfolding disruptions and mitigate their impacts on the system. A notable example of preventive

actions is allocating DERs and optimally scheduling the stand-alone operation of MGs prior to extreme events to ensure a smooth transition into islanded mode and meet local demand. Other relative measures include allocating backup generation and reserve, repositioning truck-mounted emergency generators, revising the design, siting, and construction standards, and enhancing system cyber-physical security. Proper understanding and prediction of event and system characteristics play a crucial role in implementing such measures [61].

Alternatively, or complementarily, corrective and reactive measures pertain to the post-event period and include systematic scenario-based backup plans to guarantee urgent levels of service, mitigate the aftermath of events, and restore the power system's normal operation during major contingencies. Designing and taking appropriate corrective actions like instant non-critical load shedding is pivotal in enhancing the power system resiliency [10], [62].

C. TRADITIONAL DISTRIBUTION SYSTEM RESTORATION VS MICROGRID-BASED METHODS

Traditionally, as the power system is exposed to a major contingency like a natural disaster, fault management measures, namely fault detection, fault isolation, and service restoration, are implemented. To clarify, the protection devices respond to contingency by isolating the faulty portions of the network straight away. However, depending on the sensitivity and selectivity of the protection system, some parts of the grid, so-called outage areas, may also become de-energized. To address such a situation, the service restoration procedure intends to re-energize these areas as swiftly as possible while repairing the faulty sections. Accordingly, conventional DS restoration techniques search for alternative sources (substations) and routes (tie-lines) to transmit power to the outage areas during contingencies. If adequate generation and transmission redundancy are available for the estimated repair duration, the system is reconfigured temporarily to serve loads of the outage areas [63].

Even though such an approach, based on topological modification, functions well in case of minor failures, it cannot be dependable against large-scale disturbances like chaotic weather events. For one thing, substations may be at fault in the aftermath of extreme contingencies, precluding electricity flow from the main grid. For another, in such circumstances, damaged distribution lines may give rise to the formation of de-energized, fully isolated sections within the DS. Under these circumstances, decentralized energy provision through DERs can be deemed an ultimate recourse. As the best medium to integrate and manage DERs, MGs have shown enormous potential for resilience improvement. On the whole, emerging smart grid technologies afford considerable opportunities to boost DS resilience. Using technologies such as automatic control infrastructure, advanced metering, DR programs, intelligent network infrastructure, and advanced telecommunications realizes the self-healing feature. In particular, MGs, by utilizing remote-controlled

switch devices (e.g., tie switches, sectionalizing switches) and optimally allocating DERs, enable innovative solutions to resiliency issues.

This paper reviews the research conducted on MG-based resilience enhancement schemes, techniques, and practices. As stated, the underlying principle of these studies is the potential of MGs to be operated in the islanded mode to supply loads locally. In this regard, as operational methods, the existing literature on MG-based resilience enhancement studies is surveyed under two sub-groups as follows:

1) RESILIENCE-ORIENTED MICROGRID FORMATION

These studies mainly seek to proactively find the optimal switching plan to determine the boundaries of self-sufficient MGs to be formed. If there do not exist enough remote-controlled switches within the network, this problem can be formulated as an optimal switch placement. In such an approach, MGs can be formed through either isolating portions of DS (partial coverage of DS) or fully sectionalizing DS into multiple MGs (complete coverage of DS) to supply loads locally. Implementing the former (at least) will ensure the resilience of formed MGs, whereas the latter will guarantee the whole DS (as an aggregate of formed MGs) resilience.

2) RESILIENCE-ORIENTED MICROGRID SCHEDULING

These studies generally focus on optimal energy management of existing (or to be formed) MGs to ensure their resilience in case of disconnection from the main grid and sustain the local power supply.

It should be pointed out that some studies cover both mentioned subjects, i.e., scheduling of optimally formed MGs. In addition, MGs can participate in infrastructural planning measures. These approaches mostly pertain to long-term optimal MG resilience-directional placement and DER expansion planning. The following sections of this paper move on to detail and review the literature on these two MG-based resilience enhancement schemes.

IV. RESILIENCE-ORIENTED MICROGRID FORMATION WITHIN DISTRIBUTION SYSTEM

In large-scale disturbances, like catastrophic natural disasters, multiple faults may render some parts of DS isolated and unsupplied or even fully de-energize the DS by hampering the energy flow from the main grid through substations or feeders. In such situations, traditional DS restoration techniques based on system reconfiguration may not ensure system re-energization. Here, forming MGs within the DS can be a brilliant idea. Its general concept description and relevant literature survey are presented in the following.

A. OUTLINE

With the deployment of the smart grid, and especially the ever-increasing penetration of DERs and remotely controllable switch devices, intentional and controlled islanding from RESs and dispatchable DGs is regarded as a promising

TABLE 2. Overview of literature review on the resilience-oriented MG formation.

Distinct feature	References
Uncertainty capture	[62], [71], [73], [74], [75], [76], [82], [86], [87], [92], [93], [98], [103], [105], [110]
Meshed architecture of formed MG	[62], [66], [79], [80], [95], [103]
Three-phase unbalanced network	[35], [67], [74], [82], [83], [85], [104]
Dynamic MG formation	[62], [66], [71], [73], [75], [78], [79], [86], [88], [89], [90], [91], [92], [93], [97], [103], [106], [107], [114], [117]
MERs	[62], [92], [93], [94], [95], [96], [97], [99], [103], [106], [109], [110]
NMGs / Power exchange among formed MGs	[67], [73], [80], [91], [98], [99], [102]
Cascading Failure Prevention	[62], [73], [78], [103], [104], [105], [106], [115]
Event-specific MG formation	[86], [107], [108], [109], [110]
Communication resilience	[66], [115]

approach to enhance the DS resilience against major events. A potential solution to achieve this goal is to well exploit these resources and switches by intentionally splitting the DS into multiple self-supplied MGs. As stated in the IEEE standard 1547.4 [64], dividing the DS into several MGs can improve the system's operation and reliability.

The logic behind electric service restoration through optimal MG formation is to optimally allocate resources to maximize the total weighted sum of restored loads by locally supplying them through DERs until the complete restoration of the main grid. To do so, the optimal switching plan must be conducted; if there is a lack of controllable switches, this plan will equal an optimal placement problem of sectionalizing switches.

From a practical standpoint, following a major event occurrence—assuming that the communication and monitoring system is reliable—the network configuration and system failures would be specified. After isolating the least portion of the network containing faulted zone by controllable switches, the self-healing system reconfiguration will partition the network into an optimal number of self-adequate MGs to serve loads locally [65]. However, some challenges exist in efficiently forming MGs from several RESs and DGs, especially in the case of facility destructions or communication system collapse [66].

B. LITERATURE REVIEW

In the following, the relevant literature on this topic is reviewed based on some distinct features considered in the models and mathematical formulations. Even though each paper's general description—central idea and contributions—is outlined in one subsection, it may embrace more than one. Table 2 illustrates the literature summary.

1) MICROGRID FORMATION STRATEGIES

The resilience-oriented optimal MG formation problem can be addressed through various approaches. The most important and prevailing optimal MG formation strategies are mathematical programming, heuristic search, graph-theoretic techniques, hierarchical and iterative algorithms. In most

cases, the objective of this problem is to maximize the total prioritized load to be picked up while satisfying operation and topology constraints. However, other objectives have been set in studies, as well. For instance, Osama et al. [67] propose a dynamic MG formation framework that maximizes both the islanding success probability of MGs and their self-adequacy; the latter objective is equivalent to minimizing the power exchange among MGs.

In mathematical programming, binary variables represent the 1) commitment status of energy resources, 2) switching status of the distribution lines, and in some papers, 3) status of curtailable or shiftable loads. In addition, there may be other binary decision variables in the intentionally controlled islanding problem. Therefore, in its essence, the MG formation problems are formulated as mixed-integer programs (MIPs) with different computational performances. Patsakis et al. [68] investigate the efficiency and accuracy of three different deterministic MIP formulations for resilience-oriented intentional controlled islanding problems. Generally, depending on whether the exact power flow or linearized DistFlow model [69] is used, the problem will be non-linear (MINLP) or linear (MILP), respectively. In addition, there are some general graph-theoretical and hierarchical frameworks to partition the DS optimally (see, e.g., [70], [71], [72]). The most important constraint to be met is minimizing real and reactive power mismatch in emergency cases. It can be well fulfilled by self-adequate MG formation, i.e., the optimal determination of island boundaries and resource allocation. What follows are a number of other constraints, assumptions, and key aspects of the models.

2) UNCERTAINTY CAPTURE

Another key aspect in modeling MG formation within the DS is whether to consider the uncertainties (mentioned in Subsection II-C) or not, which will result in stochastic/robust or, more frequently, deterministic problems, respectively. In a notable paper, Wang and Wang [73] develop a double-stage stochastic optimal DS operating framework as an MINLP problem comprising normal and self-healing modes. In the

case of a fault or multiple faults, the system enters the self-healing mode by optimally transforming the on-outage portion of the distribution network into networked, self-adequate MGs to re-energize as much as possible loads. The uncertainties in load and non-dispatchable generation are considered by a normal distribution and stochastic rolling horizon optimization concept, respectively.

Considering the supply-demand uncertainties, Popovic et al. [74] model MG formation as a minimax problem while minimizing the risk of unsuccessful islanding due to unmet local load. Taking into account the same uncertainties, Sharma et al. [75] develop a decentralized MAS to form self-sufficient islands with DERs. In another article, Biswas et al. [76] adopt a chance-constrained approach to model the probabilistic, optimal DS sectionalizing problem while capturing the demand-supply uncertainties.

3) MESHED ARCHITECTURE OF FORMED MICROGRID

Maintaining the radial architecture of the formed MGs is another prevalent constraint in this field, which is often ensured by graph-theoretic methods. In case of any fault at a feeder, the normally open tie reclosers of the radial networks, located at the end of feeders, are closed to enable faulted zone repair and provide service to the unaffected portion of the system [77]. In emergency circumstances, maintaining the radiality in formed MGs facilitates the system's return to normal operation mode after fault clearance [78].

However, some studies consider the meshed (ring) topology for the formed MGs. Such an architecture is highly reliable due to the capability of isolating faults using reclosers while the remaining portion of the feeder can continue to receive service [77]. For example, Lei et al. [79] propose a dynamic MG formation framework with improved radiality constraints resulting in enhanced flexibility, e.g., allocating multiple DGs to each MG and applicability to meshed architectures. As another example, Cortes et al. [80] develop a graph-theoretical plan to form MGs containing meshes and radial branches within a DS.

4) THREE-PHASE UNBALANCED NETWORK

Considering three-phased balanced DSs is another common constraint in the literature. However, distribution networks are inherently unbalanced due to random, ever-changing load demands on each phase [35], [81]. Chen et al. [35] develop a sequence of control actions for service restoration in the case of major contingencies. The proposed framework coordinates the operation of DGs and remotely controllable switches over multiple time steps concluding in self-sufficient MG formation within unbalanced DSs.

Ali et al. [82] propose a three-stage optimal DS sectionalizing method to form multiple MGs considering system unbalance and adopting a heuristic solution method. Huang et al. [83] propose a MG formation model as a Markov Decision Process (MDP) with a deep reinforcement learning (DRL)-based solution methodology. This paper uses OpenDSS [84] to calculate a three-phase unbalanced power

flow. Fu et al. [85] develop a model to sectionalize DS into multiple MGs while emphasizing the three-phase demand-side management. This paper addresses the load unbalances by optimally switching loads among phases, their possible curtailment, and dispatching DGs to enhance the controllability of the formed MGs.

5) DYNAMIC MICROGRID FORMATION

Dynamicity refers to a variability characterized by time-varying boundaries of formed MGs. In practice, as proceeding with operational and infrastructural restoration (time range of $t_3 - t_6$ in Fig. 2), the system and formed MG topology should be reconfigured to optimize the ongoing restoration. A large and growing body of literature investigates the resilience-oriented MG formation problem over multiple time steps. This involves the real-time allocation of DERs and switching operations.

In this regard, Ghassemi et al. [86] propose a two-stage stochastic MILP to tackle planning and emergency aspects of DS resilience against hurricanes. The first stage of this model issues the investment decisions on line hardening and DG installation; the second stage involves emergency response by a master-slave formulation leading to dynamic MG formation. In another double-stage stochastic MILP model, Abessi et al. [87] develop the optimal formation of dynamic MGs while introducing and investigating internal combustion engine cars as emergency energy resources for improving DS resilience. Mohsenzadeh et al. [88] propose an optimal framework to form MGs with varying boundaries while considering the DR program and optimal siting and sizing of DGs. Zhao et al. [89] propose an improved network reconfiguration model to perform dynamic MG formation. In this paper, two black-start and dispatchable modes for DGs are specified. Zhu et al. [90] propose a comprehensive dynamic MG design capable of partitioning into multiple sub-MGs and enhanced flexibilities in islanding and grid connections. Employing a DRL method, Zhao et al. [91] provide an optimal solution to the online, dynamic multi-MG formation problem modeled as a MDP.

6) MOBILE ENERGY (EMERGENCY) RESOURCES

At times, fixed DGs may not be able to reach complete load restoration, particularly in the aftermath of catastrophic events. In such circumstances, mobile energy (emergency) resources (MERs), i.e., mobile emergency generators (MEGs) and mobile energy storage systems (MESSs), can be dynamically dispatched to candidate nodes and present a highly effective and fast response. To unleash this potential of MERs, their capacity has been considered in resilience-oriented optimal MG formation.

From this perspective, Lei et al. [92] propose a two-stage framework to form multiple MGs incorporating proactive pre-positioning and real-time allocation of MEGs. The pre-positioning problem is formulated as a scenario-based stochastic problem with post-event road network damage assessments. Using this information, authors formulate the

real-time allocation problem as a deterministic MILP to dispatch MEGs and form MGs to pick up specified critical loads. Nazemi et al. [93] propose a model to optimize the formation of islanded MGs with dynamic boundaries within DS in accordance with MESSs sitting and sizing and RESS scheduling. In this paper, uncertainties are captured by a joint probabilistic problem formulation. Beginning with incomplete system information during and after a large-scale event, [94] updates the data dynamically and develops a MG formation scheme along with dispatching MERs.

Sedzro et al. [95], in a foresighted manner, co-optimize both DGs and MEGs while considering DR programs and both radial and meshed topologies for formed MGs. Due to the computational intractability of stochastic MILP problems for medium to large, more realistic power systems, Sedzro et al. [62] propose a heuristic approach to post-disturbance MG formation in three stages. Firstly, the optimal location for MEGs, considering the location of fixed DGs and demand-responsive loads after contingency, is determined. Next, non-isolated nodes are clustered into MGs with a feasible assignment of DGs via the k-means method. Lastly, the feasibility of formed MGs is evaluated with operational constraints. Bhusal et al. [96] develop a MERs sizing model and performs a network reconfiguration feasibility check via a graph-theoretical method. Lei et al. [97] propose a dynamic MG formation scheme in conjunction with dispatching MEGs and repair crews (RCs).

7) NETWORKED MICROGRIDS FORMATION / POWER EXCHANGE AMONG FORMED MICROGRIDS

While most papers seek to form self-sufficient MGs within the DS, some research works model and investigate the power exchange among formed MGs or even the formation of NMGs. Adopting a graph-theoretical approach, Arefifar et al. [98] propose an optimal DERs allocation and MG formation framework while studying energy transfer effects among formed MGs. Ding et al. [99] develop a MILP model to co-optimize the RC routing and repair time, routing and charging strategy for MESSs, and network reconfiguration leading to the formation of Soft-Open-Point (SOP)-based NMGs ([100] and [101] provide a systematic review of emerging SOP technology in DSs). Barani et al. [102] suggest a two-stage model for optimal placement of DERs and protection devices and subsequent DS partitioning into multiple MGs while considering power exchange among them.

8) CASCADING FAILURE PREVENTION

To tackle the potential risks of new outages under extended extreme events, Che and Shahidehpour [103] propose a two-stage restoration strategy. The first stage seeks to determine the optimal minimum-scale MGs topology and MERs allocation. The second stage aims to shrink the formed MGs further and reposition MERs to minimize loss of critical loads in the extended extreme event, thereby enhancing MG survivability. Another criterion to form less vulnerable MGs after natural disasters is suggested by Khederzadeh et al. [104]. In the

proposed genetic algorithm-based method, prior to system reconfiguration, the possibility of cascading failure in the formed MGs is minimized by identifying the heavily loaded lines and their tripping consequences.

Arefifar et al. [105] propose a resilient operational planning framework. In this framework, virtual supply-adequate MGs are formed by dividing the smart DS while incorporating self-healing actions like dynamic system reconfiguration and load shedding. Ma et al. [78] suggest a strategy to restrict the outage propagation incorporated in the MG formation model. To this end, a fictitious symmetric ground fault is exerted to the virtual node in the middle of each line; if the voltage magnitude of the two ends of a branch is zero, there exists a disturbance in that location, and by disconnecting that line, the load will be curtailed and fault propagation will stop. Cai et al. [106] develop a two-stage service restoration framework to mitigate the risk of subsequent power system failures in case of major contingencies. This model optimizes the proactive MG formation, as well as load switching and generation allocation sequences.

9) EVENT-SPECIFIC MICROGRID FORMATION

Recently, it has received considerable attention to devise exclusive resilience improvement strategies regarding geographical and meteorological factors. These studies require proper modeling of weather-related failure rates and evaluation of fragility curves of power system components.

Accordingly, in an event-specific study, Cahig et al. [107] propose a dynamic MG formation strategy against typhoons while modeling the disaster in a spatiotemporal manner. Similarly, Wang et al. [108] suggest a framework to evaluate the DS resilience against typhoon disasters. In this paper, the probabilistic generation model of typhoons and vulnerability model of DS lines are followed by a heuristic search algorithm to form islanded MGs within the DS. Wu et al. [109] develop an optimal MG formation scheme with MESSs, RCs, and microturbines under the contingency of forced wind power cut-off due to extreme wind speed during hurricanes. As a preventive measure, Bahrami et al. [110] propose an optimal DS sectionalizing framework prior to windstorms. This model utilizes the Markov chain model to determine the damage level done to trees and the consequent failure probability of overhead lines as inputs of the developed optimization problem.

10) COMMUNICATION RESILIENCE

Power system communication is the Achilles heel of the system during the restoration process, and a lack of resilient communication infrastructure would jeopardize situational awareness. There are several published studies describing the role and requirements of the communication system in enhancing resilience ([111], [112], [113], to cite a few). However, some studies incorporate communication resilience in the optimal MG formation problem. Chen et al. [66] propose a MILP model for radial DS restoration strategy by forming multiple self-supplied MGs. This model fulfills

communication resilience requirements by designing a distributed multi-agent coordination scheme. To reduce the computational complexity of this model, Ding et al. [114] reformulate the model proposed in [66] by lessening the scale of binary variables. To comply with the requirement of real-time status communication in the case of large-scale disturbances, Qi et al. [115] suggest a new system design including the embedment of intelligent power electronic devices and control schemes. This scheme realizes a reconfigurable system and intentional islanding of a MG or a portion of the power grid.

11) OTHER FEATURES

Derived from the modularity feature of the DS, Mousavizadeh et al. [116] propose a framework for multiple MG formation, which comprises optimal allocation of DERs and ESSs, and optimal placement of switching devices. Ju et al. [117] propose a strategy for DS sectionalizing into multiple MGs, each equipped with a local combined heat and power (CHP) unit to meet critical electrical and thermal demands. Zhu et al. [118] propose a MG formation strategy as a MILP model considering the fictitious power flow model to decrease the scale of binary variables. Some papers present optimal scheduling followed by partitioning DSs into MGs. Choobineh and Mohagheghi [63] propose a MG formation and EMS to address the electric service restoration in the immediate aftermath of a natural disaster within a distribution network. A self-healing strategy is designed by Zadsar et al. [65] as a double-layer algorithm comprising optimal MG formation and DERs management at the time of fault occurrence.

Control is the central issue in some resilient MG formation studies. Emphasizing voltage control during service restoration, Macedo et al. [119] provide a MILP model to restore electric supply by optimal network reconfiguration and formation of self-sustainable MGs. Adopting master-slave DG operation, Ding et al. [120] formulate a resilience-oriented model to partition the DS into MGs. The proposed model is to tackle the circulating current among DGs in droop-control-based methods, such that a master unit implements the voltage and frequency control while other units perform the current control within each MG.

V. RESILIENCE-ORIENTED MICROGRID OPTIMAL SCHEDULING AND ENERGY MANAGEMENT

Having discussed the details and literature on constructing MGs within a DS, this section addresses their energy management to enhance resilience. In the course of normal conditions, MGs are connected to the main grid to benefit from power exchange with the upstream network while meeting its demand. To put it another way, a MG, in an economical manner, during the off-peak price periods, purchases power from the utility grid while setting its generation to a minimum amount; conversely, its generated or stored power is sold in the peak price intervals. In normal operation, the main grid is regarded as an infinite bus with unlimited supply and demand,

maintaining the power balance and regulating the frequency and voltage of MGs.

On the other hand, islanding capability, as the vital attribute of MGs, can be deemed a solution in contingencies. In case of disturbances in the main grid, MG disconnects itself from it to afford protection to its components, like voltage-sensitive loads [121], and more importantly, to supply its loads locally. However, MGs are required to be scheduled in such a way that stand-alone operation requirements are satisfied. This section attempts to provide the outline and a survey of the literature on optimal MG scheduling in case of large-scale disturbances, the overview of which is displayed in Table 3.

A. OUTLINE

Proper energy management of MGs during unscheduled islanding events—as a response to upstream network disturbances—is highly helpful in fulfilling DS resilience. Islanded operation of MGs should be arranged such that electrical service endures as much time as possible, given that the duration of disconnection from the main grid is almost unpredictable for unscheduled islanding events.

EMSs schedule and coordinate the functioning of the dispatchable DGs, RESs, ESSs, MERs, loads, and so forth. The main challenge in this regard is the prevailing operational uncertainties and the stochasticity in the start and end times of the disturbances. To tackle this challenge, stochastic and robust frameworks are proposed to prepare the MG for unscheduled islanding events. To feed these stochastic models, a set of scenarios capturing different uncertainties with acceptable probabilities is required. These scenarios are decreased by scenario reduction techniques to make the optimization problem computationally tractable. Once the uncertainties of a specific scenario occur, the corresponding schedule is put into effect.

These frameworks mostly consider both the grid-connected and islanded operation of MGs. Usually, grid-connected operation in normal conditions is formulated by a unit commitment problem aiming at minimizing the total operation cost while dispatching the local resources and determining the power transfer with the utility grid. On the other hand, the optimal operation of MGs in islanded mode aims at maximizing the total weighted sum of served loads during upstream grid disturbance while capturing the uncertainties.

B. LITERATURE REVIEW

Regarding optimal, resilience-oriented MG scheduling and energy management, there are many operational and technical challenges to tackle. The following subsections provide a literature review on this topic regarding some specific assumptions, techniques, technologies, and constraints used in relative research works. Each paper's principal idea and contributions are under one subheading; however, it may cover more distinct features, as seen from the literature summary in Table 3.

TABLE 3. Overview of literature review on the resilience-oriented MG scheduling and energy management.

Distinct feature	References
Microgrid islanding feasibility check	[16], [24], [122], [135], [141], [156]
Uncertainty capture	[16], [23], [24], [39], [40], [59], [122], [124], [125], [126], [128], [129], [130], [131], [134], [135], [136], [138], [139], [142], [146], [152], [162], [166], [167], [168], [169], [177], [181]
Risk management	[12], [129], [130], [131], [158], [169]
NMGs scheduling	[24], [27], [59], [122], [132], [134], [135], [136], [137], [138], [139], [140], [141], [142], [163]
MERs and RCs	[139], [143], [144], [145], [146], [147], [148], [149], [150], [151], [152], [153], [154], [155], [156], [157], [158], [159], [163], [164], [165], [171]
Multi-energy MG management	[157], [158], [159], [160], [161]
DR programs and EVs	[125], [126], [131], [136], [156], [162], [163], [164], [165], [166], [167], [168]
Hybrid AC/DC MG scheduling	[24], [40], [168], [169]
Event-specific MG scheduling	[11], [12], [158], [160], [163], [170], [171], [172]

1) MICROGRID ISLANDING FEASIBILITY CHECK

In the case of disturbances in the DS, especially extreme events occurrence, the feasibility of MG islanding is of critical importance. In addition to technical constraints associated with feasible islanding, the capability of MGs to stand-alone operation mostly depends on the supply-demand balance after isolation, at least for their fixed, critical loads. Power mismatch causes frequency fluctuations, leading to major damage to the system components. Therefore, to guarantee such a transition, MGs must proactively be prepared for feasible islanding in normal operation mode, which necessitates proper generation, storage, and load scheduling.

In multi-stage optimization models, to perform the islanding feasibility check, the optimal scheduling of the normal operation mode—for specified unscheduled islanding scenarios—is evaluated in the islanded mode operation to guarantee generation sufficiency. Suppose the predicted generation and consumption of the islanded MG are not balanced. In that case, the initial solution of the normal operation mode, i.e., the schedule of generation, storage, and loads, is revised by priority using the so-called islanding or resiliency cut. This process is performed iteratively until it completely balances the supply and demand. If a specific number of revision steps does not ensure feasible islanding, the prioritized load curtailment is implemented as a last resort. Although these revisions cause a rise in the MG operation cost, they can ensure its secure islanding in an emergency, the lack of which may bring about significant socio-economic damage.

In a notable paper, Khodaei [16] proposes a robust model for centralized MG scheduling to improve system resiliency. In this model, the master controller utilizes all the normal operation scheduling solutions to determine the optimal schedule of DERs, adjustable loads, and the main grid power and examine MG capability in self-adequately supplying local loads after islanding. To capture the load and non-dispatchable generation forecast uncertainties, a worst-case solution to the resilient operation problem is considered by using corresponding load and generation in their higher and lower uncertainty bounds, respectively, in the power

balance constraint. To capture main grid interruption start time and duration uncertainties, a binary outage state is determined offline, and possible islanding scenarios are defined. The feasibility of islanding for each scenario is examined, and if there is any mismatch, the normal operation problem solution would be revised using the resiliency cut. This iterative process, in each iteration of which i) units commitment and ESSs schedule, ii) adjustable loads schedule, and iii) curtailed loads are revised, continues until power mismatches in all islanding scenarios reach zero.

In another comprehensive study, Shaker et al. [122] propose a stochastic optimization model for the decentralized, resilient operation of NMGs in post-event unintentional islanding. While emphasizing reactive power management, this model guarantees the feasibility, security, and optimality of the operation of each MG in islanded mode through three subproblems. Hussain et al. [123] propose a scheduling model for NMGs while evaluating the feasibility of each MG islanding in feeding its local critical loads by suggesting a resilience index. This model, considering supply-demand uncertainties, if necessary, revises generation and storage commitment statuses based on the resilience index.

2) UNCERTAINTY CAPTURE

Concerning the essence of resilient MG scheduling, much of the current literature on it involves uncertainties. Multi-stage stochastic and robust models have been widely used while capturing the uncertainties mentioned in subsection II-C and others.

In this regard, by utilizing the economic opportunities of MG, Gholami et al. [39] develop a double-stage stochastic resilience-directional MG scheduling framework addressing both normal operation and contingency-based uncertainties. The proposed model minimizes MG's socioeconomic cost while considering the AC operation constraints and concludes by scheduling the DERs dispatch, demand-side reserve, and power transactions with the main grid. Liu et al. [124] propose a robust MG scheduling guaranteeing system resilience while performing sensitivity analyses for different robustness

and uncertainty levels. Tightiz and Yang [125] suggest and analyze two DRL methods to be applied in resilient MG EMS while considering uncertainties. Capturing islanding duration, market price, and supply-demand uncertainties, Zografou-Barredo et al. [126] develop a robust mixed-integer second-order cone programming model to deal with the scheduled MG islanding.

Especially to tackle the uncertainties in the generation of RESs, some research studies emphasize ESSs scheduling. Liu et al. [23] propose a robust optimization model for MG scheduling while capturing uncertainties in renewable power generation and load forecasts with a proper robustness level. This paper also considers some constraints to calculate the optimal amounts of up- and down-spinning reserve for cases of islanding events to accommodate local renewable power generation and serve local load while mitigating the lost/redundant power generation at PCC. Shahinzadeh et al. [127] numerically evaluate the impact of proper estimation and selection of energy storage facilities of the islanded MGs on their uncertainties-based resilience indices. Gutierrez-Rojas et al. [128] propose a chance-constrained optimization model for MG resilient and economical operation while focusing on ESS scheduling. This paper uses machine learning models to predict some inputs of the optimization problem, i.e., MG load demand, PV generation, and supply interruption in the upstream grid.

3) RISK MANAGEMENT

MG EMSs are exposed to different types of risks which should be addressed in stochastic optimization models. Panteli et al. [12] propose a risk-based islanding strategy to isolate the vulnerable components and prevent cascading failures in the case of severe windstorms. Accordingly, operators could do so by comparing an index, indicating the impact and probability of selected failure scenarios, with a prespecified threshold. These scenarios are generated considering the weather-dependent failure probability of system components through their fragility curve.

A stochastic, least-cost MG EMS for unscheduled islanding events is developed by Farzin et al. [129]. In the proposed model, to manage the risk of high operation costs and subsequent load curtailment imposed by the uncertainties in islanding duration and load/generation forecasts, the Conditional Value-at-Risk (CVaR) index is used. Similarly, Vahedipour-Dahraei et al. [130] propose an optimal resilience-focused MG operational framework for grid-connected and islanded mode aiming to maximize MG operation's profit and manage risk. In this stochastic problem, the uncertainties in islanding duration along with prevailing prediction errors are captured, and consequent demand-responsive actions of customers are modeled. To assess the risk imposed by uncertainties and optimize the trade-off between the expected profit and its variability, the CVaR measure is used. Finally, Nourollahi et al. [131] propose a stochastic, risk-based MG scheduling for grid-tied and islanded modes, considering AC power flow and DR programs.

4) NETWORKED MICROGRIDS SCHEDULING

As stated earlier, networking MGs provides significant opportunities toward a more resilient power system as it enables individual MGs to support each other through local generation units. However, such networking poses some challenges. Data privacy issues are determining factors in the type of communication, control, and decision-making—being centralized or decentralized—which in turn affects the NMGs' operation and interaction. Also, from a realistic point of view, even post-event interactions among individual MGs and the main grid should be modeled as a strategic market game. There are some technical challenges to deal with. Networking MGs is an increasingly important practice to improve system resilience, and there is a large volume of published studies optimizing NMGs operation. Here are some research studies with explained EMSs.

An optimal normal and self-healing operation framework for NMGs connected to a common bus is proposed in [27]. According to this paper, in case of fault or generation deficiency, the MG transforms into the self-healing mode and appeals for power support from neighboring normal operating MGs. The optimal allocation of requested power among the supporting MGs is performed through a double-layer decentralized control and communication system. Ambia et al. [132] develop a decentralized control method for communicationally interlinked converters within ESSs to enable power exchange among networked hybrid AC/DC MGs in overloading conditions. In this paper, the reference power adjustment strategy of the DC-DC converter is designed to enable power redistribution from wind farms. In contrast, the bidirectional AC-DC converter control schemes tackle the voltage and frequency deviations during load restoration. A power generation and energy storage management scheme for islanded MGs clustered by tie reclosers or retrofit auxiliary distribution lines is proposed by Essakiappan et al. [133] to improve the system resilience during a transmission system outage. This operation process does not require modifying power inverter controls and can be implemented with minimal control and communication system changes. Defining a NMGs system as one MG with multiple sub-MGs, Mehrjerdi [134] proposes a resilient, centralized EMS.

In a comprehensive article, Teimourzadeh et al. [135] propose a resilience-directional triple-stage optimal scheduling model for NMGs as a stochastic MILP problem. In the first stage, the status of dispatchable DERs and optimal amounts of power generation for all DERs, power transactions of NMGs with the upstream network, and demand-side reserves under the normal operating condition are determined. Considering the first stage outcome, the second stage specifies the power transactions among MGs within the NMG system and addresses normal operation. Additionally, real-time contingency-based uncertainties associated with NMGs' unintentional islanding from the upstream grid and resynchronization events are captured in this stage. The third stage models the real-time contingency-based uncertainties in unintentional islanding of each MG from the rest of islanded

NMGs and its resynchronization considering the solution of the first and second stage problems. This paper adopted the three-point estimation technique to generate a limited number of most probable scenarios corresponding to each transition between stages to feed the proposed model. Capturing uncertainties of start time and duration of major disturbances, Ebadatparast et al. [136] propose a dynamic, stochastic MILP for optimal operation of NMGs and DS in both normal and emergency conditions.

Hu et al. [137] propose a conditional grid-assisted and self-restoration EMS for NMGs based on model predictive control and real-time market prices. By defining an index for the probability of successful islanding, indicating the capability of MGs to maintain sufficient up- and down-spinning reserve amounts and operate in a self-adequate manner, Liu et al. [138] suggest a chance-constrained optimal scheduling problem for both individual and NMGs. In a planning-oriented research study, Wang et al. [59] propose a NMGs sizing model to enhance system resilience. Alam et al. [139] propose an optimal, resilience-directional MESS placement and scheduling within NMGs, while capturing demand-supply and market uncertainties and studying the impacts of the Internet of Things (IoT) on NMG operation. To tackle the extended disconnect of NMGs from the main grid, Nourollahi et al. [140] suggest day-ahead scheduling while considering the DR program. Fesagandis et al. [141] propose a double-stage NMGs resilient, optimal operation framework comprising day-ahead grid-connected and real-time islanded modes. This paper adopts the Benders decomposition algorithm to assess the feasibility of MG islanding. Zhou et al. [142] develop a resilient NMG operation/control scheme introducing two modes of division and unification. Division mode pertains to the pre-event period in which each MG is controlled by its master controller and managed proactively to be prepared against major disturbances; during which NMGs are operated in the unification mode as integrated self-controlled, cooperating entities.

5) MOBILE ENERGY (EMERGENCY) RESOURCES AND REPAIR CREWS

As stated in Section II, repairs are inevitable in the aftermath of destructive events. Dependent on the scale of the event, these repair efforts can be substantial or minor. How to organize and route the repair crew is of great importance. Due to ongoing repairs, some parts of DS are restored as time passes; this partial service restoration should be reflected in dynamic network reconfiguration while scheduling MGs. Utilizing MERs is another highly promising approach to promote power system resilience. As in optimal MG formation to enhance the DS resilience, MERs can be employed to improve the resilience of existing MGs. Therefore, proper dispatching of these resources should be considered in either a proactive or reactive manner.

A considerable amount of literature has been published on DS restoration through co-optimizing RCs, MEGs, MESSs, and RESs [143], [144], [145], [146], [147], [148], [149],

[150], [151]. Huang et al. [149] develop a model to optimize the prepositioning and routing of MERs using data-driven and graph-theoretical methods. Considering the distribution lines and transportation network interdependence, Li et al. [150] propose a model to determine the repair and charging stations and co-optimize the RCs and MESSs dispatch. Rodrigues et al. [151] develop a model for MEG prepositioning to improve system reliability and resilience.

Another way to cope with extensive events is to deploy and manage small-scale mobile RESs. Monteiro et al. [152] investigate the role of mobile RESs in islanded MG service improvement. This paper proposes a heuristic model to allocate the truck-mounted wind turbines while developing a dynamic EMS for MG. Su et al. [153] propose an optimal routing and scheduling for small-scale mobile wind turbines, jointly operated with electric thermal storage systems, to serve multiple isolated MGs.

In case of large-scale disturbances, electric buses (EBs) can be translated to MESSs with a substantial capacity. To exploit this potential, [154] and [155] propose optimal scheduling and routing schemes for EBs with large batteries to take a role in restoring DS, which is already separated into multiple MGs powered by DGs. These papers consider the power and transportation systems constraints, as well as dynamic network reconfiguration. In another research study, Xu et al. [156] address the load restoration problem with EBs, MEGs, MESSs, and RCs, considering the dynamic system topology due to repairs and varying traffic.

6) MULTI-ENERGY MICROGRID MANAGEMENT

Natural events not only may interrupt the electric service but also jeopardize the operation of other energy systems and interconnected infrastructures. In this respect, considering the resilience of other systems, especially gas and transportation networks, and ensuring fuel security is of critical importance. What follows are examples of multi-energy MG resilient EMSs.

Wang et al. [157] propose a MILP to address the restoration of power and hydrogen DS in a hybrid and dynamic manner while considering network reconfiguration, RCs, and MESSs. Zhu et al. [158] introduce a Z-number-based technique to estimate the failure probability of transmission lines after a hurricane and provide a comprehensive DS restoration plan as a two-stage robust optimization problem while incorporating MEGs, CHP units, PV panels, and DR management. Jiang et al. [159] propose a restoration model to dynamically co-optimize the natural gas, transportation, and power DSs leading to the gas turbine scheduling and MESSs routing. Amirioun et al. [160] provide a proactive multi-energy MG scheduling to enhance the against hurricanes. This study includes event characterization, thermal and electric power flow and storage, and gas network constraints. Lastly, Masrur et al. [161] develop a resilient, optimal electric and heat dispatch model incorporating CHP units, EV charging stations, and thermal ESSs, RESs, and ESSs.

7) DEMAND RESPONSE PROGRAMS AND ELECTRIC VEHICLES

In essence, DR programs and V2G technology afford additional flexibility for utilities and operators to handle complex energy situations in cases of major disturbances. Furthermore, amid extreme events, there is a significant probability of road impediments that may hamper the dispatch of RCs and MERs and seriously delay the service restoration. In such a circumstance, DR programs and V2G technology can play a key role in meeting critical loads.

Tostado-Véliz et al. [162] investigate the role of DR programs incorporated in a stochastic, info-gap decision theory-based EMS for stand-alone MG while considering load-supply uncertainty and contingency of components failure. Papari et al. [163] propose a comprehensive, optimal NMG control and scheduling framework to deal with the post-hurricane period. This model includes EVs and DR programs, in addition to MERs, DGs, ESSs, and network reconfiguration. Considering V2G technology, Su et al. [164] put forward an optimal spatiotemporal assignment of EVs to undertake a role in supplying critical loads during an outage. Zhang et al. [165] investigate the potential of E-taxis to participate in DS restoration via V2G technology and consider network reconfiguration.

Incorporating four resilience indexes in MG optimal, stochastic scheduling, Younesi et al. [166] seek to guarantee its economic-resilient operation. This paper also models the charge/discharge power of EV parking lots along with other DERs. In a similar way, Najafi et al. [167] propose a deterministic model to numerically investigate the role of EV battery swapping stations in MG resilience.

8) HYBRID AC/DC MICROGRID SCHEDULING

As discussed earlier, by taking advantage of both AC and DC MGs, hybrid MGs have superiority in terms of integration of various DERs and operation cost and loss. Therefore, proper resilience-directional energy EMS for such MGs enjoy extra advantages. In a notable paper, Hussain et al. [24] propose a hybrid MG optimal energy management framework comprising two coordinated MILP problems for grid-connected (normal) and islanded (emergency) MG operation. In the normal operation problem, readiness for feasible islanding is modeled deterministically. In this problem, the initial solution to normal operation, including unit commitment status of dispatchable generators and scheduling of batteries, is revised to ensure feasible islanding and feeding high-priority loads by both AC and DC MGs without energy exchange with the utility grid. In the emergency operation problem, the survivability of MG in islanded mode is ensured by considering the first interval of the next scheduling window and the decision between feeding less critical loads at a given time interval and charging batteries for feeding more critical loads in later intervals. Similarly, Wang et al. [168] develop a hybrid AC/DC MG optimal operation framework while investigating the effects of preventive power importing and DR programs.

Adopting a minimax regret approach, Ebadatparast et al. [169] develop a stochastic, resilient hybrid MG scheduling framework. A robust tri-level resilient dispatch model is developed for islanded hybrid MGs by Qiu et al. [40] to tackle the meteorological disasters that occur in uncertain times. In this model, an uncertainty set based on actual situations is established to capture disaster occurrence time and duration uncertainties. In the proposed solution method, first, the bilinear constraints, associated with double uncertainties over renewable power generation and load, are linearized via the big-M method; next, the tri-level problem is transformed into a bi-level MILP problem.

9) EVENT-SPECIFIC MICROGRID SCHEDULING

As in resilience-oriented MG formation and DS partitioning, for existing MGs, it is quite sensible to establish resilient EMSs consistent with the prevalent weather events of a particular area/time. Here, investigating event characteristics, fragility curves, possible events sequence, environmental uncertainties, and meteorological forecasts are of importance, and fundamentally, statistical and probabilistic analyses play a significant role.

In a notable event-specific study, Amirioun et al. [11] develop a proactive MG management strategy against extreme windstorms involving network reconfiguration, droop-controlled DERs optimal parameter setting, conservative voltage regulation, generation reschedule, DR programs, and backup generation. In the proposed method, using the meteorological and geographical data and the concept of fragility curves, the most vulnerable distribution lines to windstorms are identified and kept out of the service prior to the event; thereby minimizing the MG vulnerability at the event onset, followed by a minimum amount of unserved load. In an attempt to address the energy system challenges during a drought, Ahmadi et al. [170] propose long-term energy system planning and a short-term EMS.

Zhu et al. [171] propose a heuristic optimization model for outage area prediction and RC routing during a typhoon event and studied it for the typhoon Kalmaegi. Eskandarpour et al. [172] formulate a single-level MILP unit commitment problem for MGs in both grid-connected and islanded modes while considering outage and component failure scenarios in the case of a hurricane. In a similar vein, [158], [160], and [163] develop EMSs against hurricanes, while [12] designs a defensive islanding strategy in case of severe windstorms.

10) OTHER FEATURES

Mottaghizadeh et al. in [173] and [174] propose secondary control schemes for voltage and frequency in islanded MGs while considering system uncertainties and communication deficiencies. Oliveira et al. [175] suggest an operator-friendly control scheme for islanded MGs to maximize the prioritized load supply time while minimizing operation costs in emergency scenarios. In an investigation into MG resilience, Bassegy et al. [176] model the black start of islanded MGs considering the interoperation of multiple DGs using

droop-control. Nie et al. [177] propose a DRL model based on MDP to perform a dual control on islanded MGs' supply- and demand-side.

In an investigation of power system protection and resilience, Elyasichamazkoti et al. [178] propose a MILP model to optimize the under-frequency load shedding relay settings, based on the rate of change of frequency, after an islanding event. Xu et al. [179] develop an unbalanced DS restoration scheme placing emphasis on PV generation uncertainties. Only considering DERs, Wang et al. [180] quantify the scheduling rationality of different sources to maximize the amount and speed of load recovery. Lastly, Spiegel and Strasser [181] develop a hybrid model for proactive, resilience-oriented MG scheduling combining mathematical programming (a sensitivity-based method) and heuristic optimization (a tree-based method).

VI. FUTURE RESEARCH DIRECTIONS

Several questions and challenges remain to be addressed. Therefore, it is recommended that further research be carried out as listed in the following:

- As stated earlier, the resilience-directional MG formation is originally modeled as an MINLP which is NP-hard, combinatorial problem. For one thing, mathematical solution methods, concluding in globally optimal system reconfiguration, entail considerable computational capacity and hardly realize the quick service restoration. For another, although heuristic and brute-force search approaches may not guarantee the globally optimal solution to the problem, they can alleviate the urgent need for a prompt solution. Therefore, more research on mathematical optimization may lead to performance improvement and fulfill the need for a globally optimal, near-real-time solution. Another future study could focus on a numerical and system-specific investigation to clarify whether a mathematical or heuristic approach should be implemented to choose between solution accuracy and the time required to find a solution.
- MGs within an NMG system and their upper system possess different proprietors. On the other hand, some MGs may be less susceptible to damages stemming from extreme events through better maintenance, protection, or even geographical advantages. In such a system, and especially under prolonged events, normally operating, less susceptible MGs may not be inclined to participate in decentralized resilience enhancement strategies based on NMGs cooperation. In terms of directions for future research, the standardized financial policies of such strategies could be entirely addressed in order not to be evaded by less susceptible MGs serving on-outage MG.
- As noted previously, the selection of the uncertainty set determines the extent to which the output of the stochastic scheduling model is conservative. Robust optimization models consider worst-case scenarios, providing the

most conservative solution to a MG scheduling problem, whereas it is desirable to take into account only the most probable scenarios. To do so, further research on data-driven methods—using historical records and system information—could lead to more practicable and less conservative models.

- Extended natural disasters, especially cyclone events, may give rise to WTs destruction or render PV panels inoperative due to diminutive solar irradiance. On the other hand, as stated in the previous paragraph, non-renewable energy sources may not function due to damages inflicted on lifelines. In such a chaotic situation, MERs and ESSs can represent a promising approach in supplying loads. Therefore, it would be a fruitful area for future research to propose strategies predominantly based on MEGs and ESSs.
- As mentioned earlier, due to ever-changing single-phase loads, DSs are inherently unbalanced. Although three-phase, unbalanced system models increase the scheduling problem intractability, further modeling work will have to be conducted considering this issue to achieve a more practical solution for MG scheduling. Additionally, further research can be undertaken to understand better how the load demand changes for each phase under large-scale disturbances; in other words, to capture the per-phase load uncertainty.
- Almost all the resilience enhancement techniques necessitate a secure cyber communication network. There is, therefore, a definite need for further investigation of the requirements for a resilient communication system (considering components of both supervisory control and data acquisition (SCADA) system and wide-area measurement system (WAMS)), paralleled by power system resilience studies.
- Most of the proposed MG-based solutions to system resilience make use of complete network information and system status in pre-, on-, and post-event phases. Whereas in practice, due to the time-consumingness of the system damage assessment process or even likely partial functionality of the communication system, complete real-time information may be lacking. Therefore, it would be interesting to carry out further research in this field using incomplete information.
- Regarding distinct geographical features of different locations, more region-specific research is required to enhance power system resilience. Apart from infrastructure resilience enhancement methods, which are obviously dependent on geographical and meteorological characteristics of the region, operational measures should also be investigated in such a manner.

VII. CONCLUSION

Recent trends in extreme natural events and cyber-physical attacks have led to a proliferation of studies aiming at improving power system resilience. Central to the entire discipline of the operational resilience of the power system is making

optimal use of MGs. This work contributes to the research field of MG-based resilience enhancement methods by providing a systematic and updated literature review. Distinctive from other review papers in this field, this study surveys the literature under two main sections of resilience-oriented MG formation and energy management; each of which is further partitioned into multiple subsections by specific features of different technologies, practices, techniques, methods, and concepts. These features are studied under multiple aspects of problem modeling and formulation and various approaches to address resilience issues including but not limited to NMGs, control schemes, communication resilience requirements, hybrid MGs, DR programs and EVs, multi-energy MGs, dynamic optimization schemes, and MERs. In the hope of providing an opportunity for further advancement, this research will serve as a base for future studies in these fields.

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