Networked Microgrids for Grid Resilience, Robustness, and Efficiency: A Review

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***Abstract*—Networked microgrids (NMGs) are clusters of microgrids that are physically connected and functionally interoperable. The massive and unprecedented deployment of smart grid technologies, new business models, and involvement of new stakeholders enable NMGs to be a conceptual operation paradigm for future distribution systems. Much work needs to be done, however, to enable NMGs to achieve seamless coordination, including physical, communication, and functional integration. In this paper, we review and summarize the state-of-the-art methodologies for operation and control of NMGs. We also specifically discuss the notion of dynamic boundaries for advanced microgrid applications. In addition, we introduce the opportunities, challenges, and possible solutions regarding NMGs for improving grid resilience, robustness, and efficiency.**

***Index Terms*—distribution systems, networked microgrids, dynamic boundary, resilience, restoration**

I. INTRODUCTION

Modern distribution systems are evolving with the massive and unprecedented deployment of smart grid technologies, new business models, and the addition of new stakeholders. Both utilities and customers are provided with more options for managing their assets. From an overall system perspective, these technologies and business models must be coordinated toward one mutually beneficial goal for both utilities and customers, that is, the improvement of grid resilience, robustness, and efficiency in response to various grid operating conditions. Next-generation distribution systems will integrate up to 100% penetration of renewable energy [1] by leveraging emerging technologies (e.g., distributed energy resources[DERs], energy storage, and demand response) and adopting various operational concepts (e.g., microgrids, virtual power plants [VPPs], and energy hubs).

While most technologies and business models are primarily designed to improve grid efficiency and customer experience, grid resilience is becoming a growing critical concern that must be addressed to achieve the goal of grid modernization. Cutter *et al.* [2] state that grid resilience is becoming an imperative concern because of the increasing frequency and severity of disastrous events. Existing outage and disaster management systems, unfortunately, heavily rely on manual communications and the experience of system operators [3].

The urgent need both for incorporating a high penetration of DERs and for enhancing grid resilience requires distribution systems to be managed in an efficient and secure manner. However, conventional distribution management that features solely centralized supervision and control inherently lacks the scalability and operational flexibility needed to effectively coordinate resources in case of large-scale blackouts and limited communication resources, which can be caused by natural or man-made disasters (e.g., extreme weather events or coordinated cyber-physical attacks) [4]. On the other hand, a hierarchical situational awareness and control architecture serves as a viable solution to address the aforementioned challenges by incorporating distributed entities to manage the complexity, with each entity communicating with neighboring units only over peer-to-peer local communication [5]. As an emerging operation paradigm in recent years, microgrids provide a potential solution by constructing a hierarchical infrastructure to manage distribution systems with DERs. The official U.S. Department of Energy (DOE) definition of microgrid [6] is "a group of interconnected loads and distributed energy resources 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." Microgrids feature both grid-following and grid-forming operation modes, allowing them to connect and disconnect from the main grid. In case of grid outages, microgrids can operate as an island to continuously support internal customers, thus significantly improving grid resilience as a whole.

The concept of networked microgrids (NMGs) refers to a cluster of microgrids that are physically interconnected and functionally interoperable. In the paradigm of NMGs, multiple microgrids, either with fixed electrical boundaries or dynamic

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boundaries through distributed and/or centralized intelligence, are connected to distribution feeders through the points of common coupling (PCCs). As a conceptual operation paradigm for future distribution systems, NMGs can be coordinated at a higher level to act as an integral part of grid operation by providing advanced ancillary services and delivering multiple operational benefits for stakeholders [7].

Some utility companies are actively adopting NMG technologies. Commonwealth Edison, commonly known as ComEd, started to build one of the first utility-scale "microgrid clusters" in the nation in 2018 [8]; this effort focused on the cluster of the Bronzeville microgrid and the campus microgrid at the Illinois Institute of Technology (IIT) in Chicago [9]. Its performance and impact, including a cost-benefit analysis, will be studied over approximately 10 years to valuate and justify the effectiveness of NMGs. Another utility, on the east coast, ConEd, is collaborating with the developers of Hudson Yards [10] (i.e., a large and private real estate developer in the west side of Manhattan) to create a service design that enables the properties within its territory to function as microgrids and facilitates a seamless transition between island mode and grid-connected operation modes [11]. The Chattanooga (Tennessee) Electric Power Board (EPB) and its partners worked on a project that enables the microgrid to expand or contract (using automated switches) boundaries based upon customer load, solar photovoltaic (PV) forecast and battery state of charge [12]. A pilot site of the developed PV-battery-energized microgrids is located at the Chattanooga airport.

In addition, there has been field deployment of "nested" microgrids. A summary of industrial microgrids and vendors of microgrid solutions is provided by Lubkeman and Julian [13] and Sam [14], including ABB, Siemens, S&C Electric, and the like. The New Paltz Microgrid project [15] proposes to use a "nested microgrid" to maintain energy supply to critical town services in the Stage-I NY Prize Competition administered by NYSERDA [16]. The proposed nested microgrid encompasses 10 independent zones or nodes, each with its own energy resources to serve one or more of the critical facilities within its geographic footprint. The Olney Town Center Microgrid project [17] is part of a DOE technology research program to design a microgrid platform that can help communities become more resilient. The microgrid is arranged into several zones based on the distribution of DERs and critical loads. The primary purpose is to develop community microgrid control systems and designs capable of reducing the outage time of critical loads by 98%, with a 20% reduction in emissions and a 20% improvement in system energy efficiencies.

The academic community has conducted extensive studies on individual microgrids [18][19]. The operation and control strategies for NMGs, however, have not been thoroughly investigated in the literature. In this paper, we review and summarize the state-of-the-art methodologies regarding operation and control of NMGs. We also specifically discuss the notion of dynamic boundaries for advanced microgrid applications. In addition, we introduce the opportunities, challenges, and possible solutions regarding NMGs for improving grid resilience, robustness, and efficiency. Finally, we envision potential applications of NMGs and provide a future outlook on NMGs.

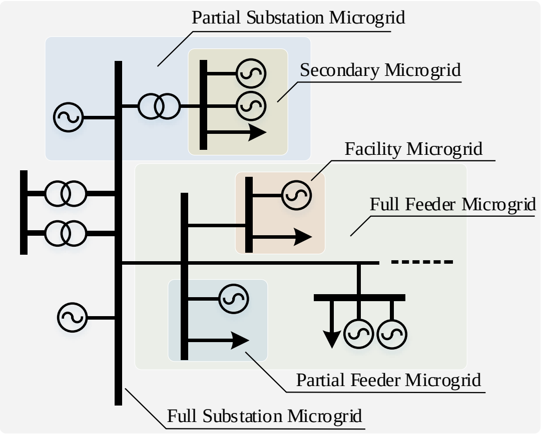


Fig. 1. Example of different types of microgrids in distribution systems (adapted from *IEEE Standard 1547*).

II. NMG FUNDAMENTALS

In this section, the fundamental knowledge of NMGs is reviewed in terms of formation, integration scheme, operation mode, modeling, and testing.

A. *Formation of Networked Microgrids*

Microgrids exist in various forms of distribution systems. Adapted from *IEEE Standard 1547*, Fig. 1 shows examples of different types of microgrids in distribution systems, with each microgrid having a well-defined electric boundary [20]. A centralized microgrid controller (MGC) coordinates all the components within its electrical boundary. Meanwhile, it can serve as an intermediate agent to communicate with peer microgrids and system-level supervisory and control systems (e.g., SCADA and distribution management system [DMS]) through designated or public communication networks in real time [21]. The proprietary information of each microgrid may or may not be shared with other microgrids and distribution system operators DSOs). Only subscribed information is exchanged among MGCs, which in turn (1) communicate with the NMG control function if these MGCs are centrally managed, or (2) serve as a master or slave NMG controller if these MGCs are managed in a distributed manner.

Instead of having each microgrid disconnected from the main grid in emergency conditions, NMGs allow some microgrids to stay connected and interconnect with other microgrids by strategically switching surrounding switches. As an example, in Fig. 1, it is assumed the facility microgrid and the partial feeder microgrid disconnect from the feeder when faults happen on the substation until the fault is cleared and the substation is re-energized. With the NMG concept, both microgrids connect back to the feeder right after the feeder is isolated from the fault by opening the breaker at the head of the feeder. In this way, a temporary full feeder microgrid is formed, and all the loads on the feeder are restored.

NMGs can be formed and operated in multiple manners, depending on the technical connectivity, ownership models, and associated operational objectives. Essentially, microgrids interconnect and eventually form NMGs to exchange electric power at different time scales, for example, to improve transient stability within seconds, to optimize power flow every few minutes or hours, and to provide sustained power supply for customers affected by outages [7].

Depending on the operational flexibility, NMGs can be categorized into two types: NMGs with fixed boundaries and NMGs with dynamic boundaries.

1. Networked Microgrids with Fixed Boundaries

NMGs with fixed boundaries are clusters of interconnected microgrids enclosed by a merged electric boundary with each microgrid having a fixed electric boundary. As shown in Fig. 2, multiple microgrids are interconnected to a segment of a distribution feeder to form NMGs to balance the load demand. The boundary of NMGs is the merged electric boundary defined by the opened switches on both sides. The electrical boundary of each microgrid, including all the components (e.g., generation sources, loads, and controllable devices) residing in the service territory, is naturally defined by its PCC(s). In emergency conditions (e.g., internal faults), each microgrid disconnects from the main grid while supplying customers only within their electric boundary. For example, as shown in Fig. 2, each microgrid opens its PCC upon detecting a fault and interconnects when the fault is cleared.

2. Networked Microgrids with Dynamic Boundaries

NMGs can be formed by dynamically adjusting the boundaries of microgrids and power sources with frequency and voltage regulation capabilities. A virtual microgrid (VMG), which can include a nested microgrid and/or DER, can connect to distribution feeders through one or more PCCs. The boundaries can be changed by operating the associated switchgear, which can serve as the PCCs for the temporarily formed microgrids. The NMGs with dynamic boundaries represent an even more flexible operational paradigm by enabling both individual microgrid and NMGs to change the electric boundary dynamically. NMGs of this type leverage two operational concepts: dynamic boundary and VMG.

Dynamic boundary, as an emerging conceptual capability of microgrids [22], allows a microgrid to expand or shrink its electrical boundary by including or excluding part of utility's network beyond PCCs and to dynamically change the boundaries for various operation purposes [12], [23]–[26]. NMGs with dynamic boundary capabilities can fully utilize the excessive generation of local DERs, as well as provide operational redundancy in case of loss of centralized control. Note that the concept of dynamic microgrids can be naturally derived from grid sectionalization approaches [27]. Rather than focusing on fixed electrical boundaries of conventional static microgrids, dynamic microgrids focus on furthering the operational flexibility of microgrids by adjusting their electric boundaries dynamically. In contrast to conventional static configurations, dynamic microgrids aim at a self-organizing framework of DERs and loads (especially critical loads) and at hosting grid assets with versatile control functions for significant grid resiliency enhancement.

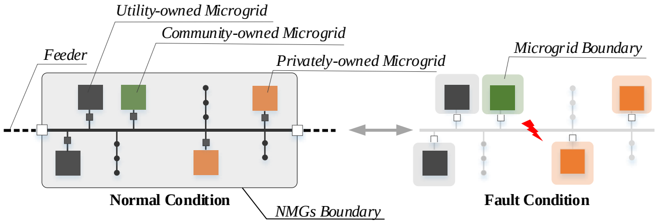
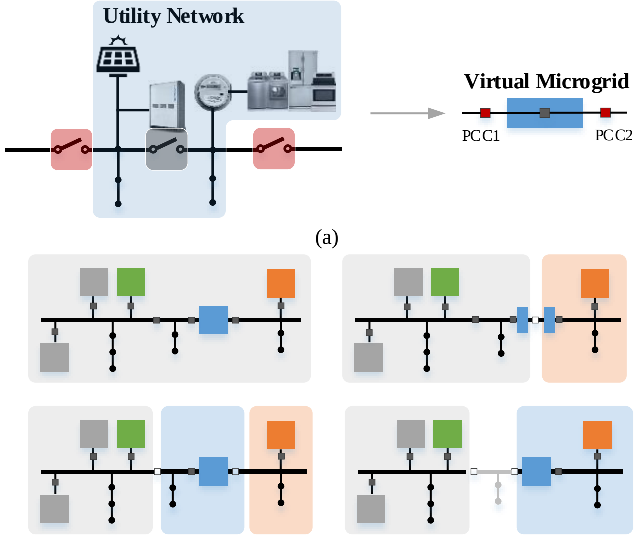


Fig. 2. Formation of NMGs with fixed electrical boundaries. All microgrids interconnect under normal conditions and disconnect from the main grid under fault conditions.



(a)

(b)

Fig. 3. Formation of a virtual microgrid with multiple PCCs: (a) concept of virtual microgrid and (b) boundaries of NMGs change dynamically under varying operation conditions.

Through telecommunication systems, a VMG can comprise various components owned by multiple stakeholders and operated in different modes.. The VMG can coordinate some or all of these components, depending on the observability and controllability of each component, such that the VMG can act as a controllable entity that can receive and act on an external control signal [28][29]. A VMG is a concept similar to that of a VPP, but with grid-forming capability, clearly defined electric boundary, and more heterogeneous components [30].

Fig. 3(a) shows that a segment of utility feeder can be potentially grouped and operated as a VMG, with the boundary defined by switches (i.e., PCC1 and PCC2). Note there is also a switch inside this VMG, which can act as a PCC and make it possible to further divide the VMG into two new VMGs. Fig. 3(b) shows the boundaries of NMGs can change dynamically under varying operating conditions. Note the VMG (i.e., the blue block) can be divided by opening the internal switch, so each part can be supported by other microgrids.

Based on the concept of a VMG, distribution systems can be managed in a divide-and-coordinate manner by logically partitioning the system into multiple interconnected VMGs, with each VMG managed by a virtual MGC in parallel with other VMGs. In emergency conditions, VMGs can be physically isolated from the main grid just like a traditional

TABLE I. CHARACTERISTICS OF MICROGRID, VIRTUAL MICROGRID, AND NETWORKED MICROGRIDS

	Ownership		**Interconnection Point**		**Boundary Operation**			**Microgrid Controller**			**Control Capability**	
	Individual	Mixed	PCC	Boundary Switch	Always Fixed	Can Expand beyond PCC	Separate and Merge	MGC	Local IED	Control Center	Grid-Forming	Grid-Following
Microgrid w/ FB	x		x		x			x			x	x
Microgrid w/ DB	x	x	x	x		x		x		x	x	x
VMG	x	x		x			x		x	x	x	x

microgrid. In addition to forming VMG by DSOs, third-party entities can aggregate local resources to form VMGs on their own. While VMGs traditionally have fixed electric boundaries, a VMG with dynamic boundary capabilities can maximize the flexibility provided by internal resources.

To further clarify these concepts, **Error! Reference source not found.** summarizes the characteristics of microgrids, VMGs, and microgrids with fixed boundaries (FB) and dynamic boundaries (DB).

3. Nested Microgrids and Multi-microgrids

There are multiple concepts similar to the definition of NMGs in the literature. Typically, nested microgrids [14] and multimicrogrids [31] are the most frequently mentioned terminologies, which refer to the interconnection of multiple microgrids into one network through electrical links to facilitate power exchange and improve energy efficiency. Although these concepts can be interchangeable with NMGs in some cases, certain characteristics differentiate NMGs from nested microgrids and multimicrogrids.

The most significant similarity is that the boundaries of nested microgrids and multimicrogrids are fixed, which is similar to NMGs with fixed boundaries. In this sense, the control and coordination methodologies developed for nested microgrids and multimicrogrids can be normally adapted for controlling and coordinating NMGs with fixed boundaries. On the other hand, NMGs with dynamic boundaries and VMGs further expand operational flexibility by fully utilizing the grid asset. In this sense, the operation philosophy of NMGs could support forming and managing nested microgrids and multimicrogrids, as well as the boundaries of these microgrids to transit from one configuration to another.

In addition, a microgrid can be physically "nested" inside another microgrid. For example, in Fig. 1, the secondary microgrid is nested inside a partial substation microgrid, a full substation microgrid or both. In this sense, the "nested" microgrid is connected through PCCs and acts as a controllable entity from the perspective of the control center and its parent microgrid.

B. Integration Scheme

NMGs must integrate with distribution systems and the control centers from multiple perspectives. The integration scheme may be different depending on the type of NMG:

(1) Physical integration. NMGs with fixed boundaries are physically integrated from microgrids with well-defined electrical boundaries. PCCs of NMGs implement physical connection and disconnection through the switchgear. However, NMGs with dynamic boundaries can be potentially integrated by closing and opening the switchgear installed throughout the distribution network. The switchgear can be operated by either the PCCs of individual microgrids inside NMGs or the control applications in DMS.

(2) Communication integration, Communication capability is critical for NMGs to perform designated functions. Depending on the operational objectives to be achieved, NMGs should communicate measurement data and status with the control center and field devices accordingly. As shown in Fig. 3, NMGs with fixed boundaries normally use propitiatory or public networking technologies to communicate with each other and the control center. NMGs with dynamic boundaries require additional communication integration between MGCs of individual microgrids and field devices. For NMGs consisting of multiple VMGs, field devices normally communicate with the virtual MGCs through the utility's proprietary network using industrial protocols. Virtual MGCs can be implemented either in the control center for centralized management or in the intelligent electronic devices (IEDs) for distributed management. The communication performance of the centralized control architecture is limited to bandwidth, latency, and scalability issues. Schneider *et al.* [32] introduced OpenFMB Harness and a distributed power system control architecture that can coordinate centralized and distributed control systems and hence increase operational flexibility. Harmon *et al.* [33] introduced a cloud-based and hybrid wireless communication framework to support the NMG operation concept.

(3) Functional integration. The value streams provided by NMGs can be realized only through functional integration among individual microgrids and the control center. In addition, to support various NMGs functions locally among individual microgrids, various systems and applications in the control center can integrate NMGs by providing supplemental and mission-critical capabilities.

C. Operation Mode

Depending on the control philosophy and specific system operation condition, NMGs support a variety of operation modes that can be leveraged to improve grid resilience, robustness, and efficiency [7], as follows:

(1) Centralized dispatch mode. In this mode, a centralized controller (e.g., DMS) can manage NMGs through the utility SCADA system. A set of system-level applications can perform dispatching and scheduling tasks considering the overall system, weather, and market conditions other than NMGs. If necessary, the centralized controller can strategically disconnect some microgrids for maintenance and safety

reasons.

(2) Distributed operation mode. Under this mode, NMGs coordinate participating microgrids without a centralized controller. The coordination can be achieved through a variety of methodologies. In addition, the coordination must be aligned with the operational goal according to specific operational scenarios.

(3) Ride-through mode. Under this mode, NMGs can ride through disturbances such as fault, low voltage, and frequency fluctuations.

(4) Black-start mode. In case of large-scale and long-duration power outages with the power network completely de-energized, microgrids with black-start capability first start up and then provide cranking power to distributed generators (DGs) in other microgrids, as well as energize the power network and customers.

NMGs can strategically operate in multiple modes to achieve the operational objectives under varying system conditions, as shown in Fig. 4.

D. *Modeling and Simulation*

Modeling and simulation is a key component for mathematically formulating and validating the control and associated elements of NMGs.

At least three levels of model fidelity are required in the modeling of NMGs [7], for different development objectives. The model with the lowest fidelity focuses on the quasi-steady-state power flow and ignores high-frequency transients; it is suitable for global design and optimization, such as the sizing of microgrid components [34] and developing energy management strategies. The model with higher fidelity retains the dominant transient response characteristics and is therefore suitable for the distributed control system design and refinements for optimal energy management analysis. The model with the highest fidelity is needed for a final evaluation of closed-loop stability and other detailed power grid performance [35], [36].

Simulation is another piece essential to verifying the performance of NMGs. A MATLAB/Simulink-based simulation tool is developed based on a model using the Euler integration method [37] to test scalable control and optimization algorithms. Barnes *et al.* [38] performed numerical experiments to explore the underlying parameters of NMG upgrades and the trade-off between cost and resilience improvement. Wu *et al.* [39] performed time-domain simulations and experiments on NMG test systems using a two-layer distributed cooperative control method. Zhou *et al.* [40] performed time-domain PSCAD/EMTDC simulations using flexible division and unification control strategies for resilience enhancement in NMGs.

III. NMGs FOR ENHANCING GRID RESILIENCE

The value of individual microgrids for improving grid resilience has been widely recognized in recent studies, for example, [41]–[44]. Some states and utilities have adopted microgrids of varying configurations. However, the technical, regulatory, and financial barriers to implementation still need further discussion and investigation, for example, [45], [46]. In the case of large-scale outages, operating distribution systems based on the concept of NMGs can further enhance grid resilience, rather than utilizing individual microgrids or traditional outage management practices.

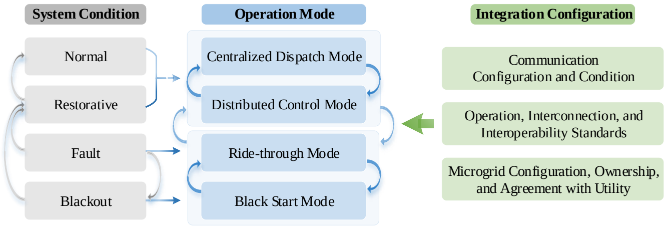


Fig. 4. Operation modes of NMGs

In this section, the challenges and existing solution methodologies of using NMGs for improving grid resilience are reviewed. In addition, the existing work that can be adapted to further facilitate the use of NMGs for grid resilience enhancement is reviewed based on three temporal stages (i.e., investment planning, pre-event preparation, and post-event operation).

A. *NMGs for Grid Resilience: Operational Principles*

NMGs can assist in grid resilience enhancement based on the following operational principles depending on the type of boundaries.

1. NMGs with Fixed Boundaries for Resilience

NMGs with fixed boundaries enable the coordination among microgrids to maximize the utilization of surplus power sources for balancing the load demand. In case of large-scale power outages caused by natural disasters, the lack of power availability poses challenges for supply continuity and customers' survivability for conventional restoration strategies that assume most utility power sources are working and stay connected [47], [48], which cannot hold in the case of natural disasters. In addition, individual microgrids normally operate in an islanded mode upon detection of outages, and thus they may be subject to insufficient generation over a long time horizon [49]. NMGs allow microgrids to exchange power through the utility's circuit so that more load demand can be balanced from the system-wide management. Farzin *et al.* [50] justified the reliability performance improvement of multiple microgrids operated as NMGs in terms of load curtailments and other reliability indices.

Coordination of NMGs with fixed boundaries is relatively straightforward, and it can be formulated as a typical operational problem. The main challenge in this regard is how to coordinate the individual microgrids inside NMGs to dynamically exchange active and reactive power through the electric distribution network. Existing work can be generally categorized into rule-based control methods [51], centralized control methods [23], [49], [52] and hierarchical control methods [50], [53], [54].

2. NMGs with Dynamic Boundaries for Resilience

The critical flexibility provided by NMGs with dynamic boundaries is needed to coordinate with DSOs and utility assets to perform advanced black-start and restoration capability. The original microgrids, as well as other individual DERs with black-start capability, can be coordinated to sequentially energize the system from a blackout state (i.e., black start) in a centralized or distributed manner. In addition to exchanging active and reactive power through PCCs, individual microgrids inside NMGs can expand the electrical boundary to energize external circuits (e.g., line segments and customer loads) by operating the switches. In this sense, NMGs can restore more customer loads even if they are not regularly serving those customers. During the restoration process, neighboring microgrids can even transfer or exchange circuit segments and loads by opening/closing the switches on the boundaries, to achieve continuous load balancing considering resource availability and other uncertainties. The greater flexibility provided by this scheme can be more adaptable to various outage and damage scenarios and spatial and temporal diversity of generation and demand. The main challenge is how to determine the energization sequence and dispatch various resources over a time horizon. Some existing studies include those by Li *et al.* [23], Farzin *et al.* [53], Resende *et al.* [55], Chanda and Srivastava [56], and Schneider *et al.* [57]. Castillo [51] assessed the benefit of coordinating microgrids as black start resources for an Independent System Operator/Regional Transmission Organization (ISO/RTO) in response to natural disasters. The optimal reconfiguration of the grid to form multiple microgrids can be obtained by using the optimization method, e.g., Chen *et al.* [27], Wang and Wang [58], and Arif and Wang [59]. Ambia *et al.* [60] introduced a formation approach to form NMGs including nested microgrids. In addition, the sequential switching operation for the optimal reconfiguration can be obtained by modeling the switching and energization logic using binary decision variables, e.g., Chen *et al.* [61]–[63]. The boundary of microgrids can also be adjusted in coordination with the repair process of the crew and mobile generation resource dispatch to fully utilize the DERs deployed in the distribution grids, for example, Lei *et al.* [52], Arif *et al.* [64], and Chen *et al.* [65].

B. Resilience-Centric Paradigm Using NMGs: State of the Art

Given the significant potential provided by NMGs for improving grid resilience, a resilience-centric paradigm that involves three temporal stages is introduced in this subsection, namely, investment planning, pre-event preparation, and post-event operation, as shown in Fig. 5. Most existing work regarding distribution resilience can be categorized into the aforementioned stages. Although the research on NMGs is still limited in the literature, related work associated with microgrids and DERs for resilience can be adapted to fit the context of NMGs, and hence is reviewed in this subsection with the potential adaptions discussed.

1. Investment Planning Stage

At the planning stage, infrastructure-hardening strategies and flexible resource deployment are the two general measures for enhancing grid resilience. The hardening solutions aim to enhance the robustness and resistance to the impact of extreme events. The options in infrastructure hardening include undergrounding cables to replace overhead conductors, upgrading the components with stronger and more robust structure and materials, elevating substations, managing vegetation, relocating facilities, building redundant components and networks, and so on [48], [66]. These methods can be applied to microgrids and/or other parts of the distribution grid so that the impact of catastrophic events on the supply continuity can be mitigated.

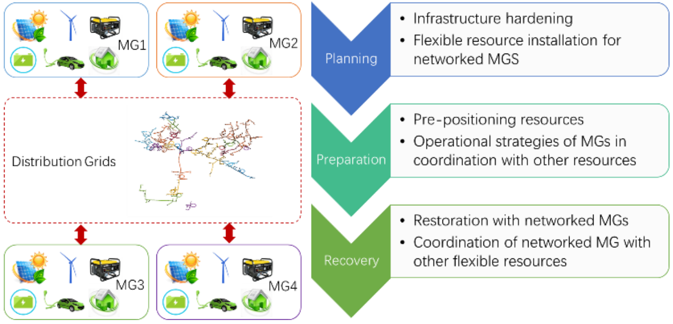


Fig. 5. A resilience-centric paradigm based on NMGs

Flexible resource deployment aims to enhance operational resilience; that is, these resources provide operational flexibility to facilitate the response and restoration of the grid with the unfolding event, and ultimately "turn on the lights" as fast as possible. One type of flexible resource is distributed generation, including backup generators, energy storage, and mobile generators. These resources can be managed by microgrids to serve the load after the event. Remotely controlled automated switches are also important because they can change the network topology to "reroute the power" and achieve the dynamic boundary microgrids.

However, it is not cost-effective to harden all the components and install unlimited flexible resources because of the budget constraints of utilities. Several studies have developed resilience-oriented optimal planning strategies, for example, Arefifar *et al.* [67], Ma *et al.* [68]–[70], Tan *et al.* [71], Yuan *et al.* [72], Zhang *et al.* [73], Lei *et al.* [74], and Xu *et al.* [75]. Lei *et al.* [74] and Xu *et al.* [75]developed the optimal placement of remotely controlled automated switches by upgrading existing manual switches considering restoration, reliability, and economic requirements. The planning stage should also consider the impact of the decision on grid operation. In the literature, multistage optimization models are normally adopted to model the uncertainty factors of extreme events. For example, Yuan *et al.* [72] formulated the problem of hardening of distribution lines and distributed generation resource allocation to minimize system damage as a two-stage robust optimization, in which the multiphase- and multizone-based uncertainty set is designed to capture the spatial and temporal dynamics of uncertain natural disasters. Ma *et al.* [68] formulated the optimal hardening strategy as a tri-level optimization problem to minimize grid hardening investment and load shedding in extreme weather events, and solve the optimization problem using a greedy search algorithm. Ma *et al*. [69], [70] applied two-stage stochastic mixed-integer optimization for hardening distribution lines and placement of Ma *et al*. developed DGs and automated switches and a computationally efficient progressive hedging algorithm [70] and a dual decomposition algorithm with branch-and-bound [69] to solve the problem in which both stages have integer variables. Tan *et al*. [71] also considered the repair process in the second stage of the stochastic optimization model. In addition, the deployment of new technologies can facilitate resilience improvement. For example, Issicaba *et al.* [76] and Nascimento *et al.* [77] investigated the long-term impact of under-frequency load shedding (UFLS) on reliability. UFLS, which is a traditional protective technology used in transmission systems, could be applied in distribution systems to coordinate with intentional islanding by balancing the load demand and boosting system frequency.

2. Pre-event Preparation Stage

During a disastrous event and the aftermath, resources in distribution systems are usually limited and hard to supplement because of degraded transportation networks. The lack of resources is a major challenge for utilities to conduct effective restoration and recovery processes [78]. In this sense, strategic prepositioning of various resources, including repair crews and equipment, as well as mobile generation resources should be planned before the disaster hits the service territory. In addition, proactive operation, for example, network reconfiguration, turning off of vulnerable components, generation redispatch, parameter setting for demand-side resources and energy storage, and the like, can help mitigate the damage of the events to the grids. The forecast of the upcoming extreme weather event and fragility analysis can provide information to identify possible vulnerable areas/components, and this information can be utilized for prestaging resources and proactive management strategically. Note that for different extreme weather events, preparation strategies may vary.

Studies in the literature usually apply one or multiple proactive strategies to become well prepared for the upcoming event. Khodaci [79] and Gholami *et al.* [80] used energy scheduling of microgrids as measures to mitigate the impact of upcoming disasters. Gao *et al.* [78] and Lei *et al.* [81] strategically prestaged mobile energy resources (e.g., truck-mounted mobile generators [81] and electric buses [78]) so that these energy resources can serve more load for post-event restoration. Amirioun *et al.* [82]developed proactive management of microgrids against windstorms by utilizing network reconfiguration, generation dispatch, conservation voltage regulation, demand-side management, and so on to reduce the loss of load under the worst case. Amirioun *et al.* [83] developed a proactive strategy using network reconfiguration, energy storage commitment, and demand-side resources for flooding hazards.

3. Post-event Operation Stage

The top priority of utilities after natural disasters is to restore the energy supply as much as possible by utilizing the undamaged generation and infrastructure to recover the grid and repair the damaged components as fast as possible. Microgrids, either via existing microgrid with a fixed boundary or dynamically formed microgrids, can facilitate this target. The decision making for multiple flexible resources, including DGs, switches, repair crews, and so forth, can be formulated as optimization problems with various resilience-oriented objectives. Several studies in the literature discuss this methodology, for example, [22], [23], [27], [48], [51], [54], [57], [58], [60], [61], [62]–[64], [83]–[89].

To make the operational decision making feasible, various operational constraints should be satisfied. One important operational constraint is to guarantee that the voltage at each node is within certain ranges, so the power flow model should be integrated into the optimization formulation. The iteration-based distribution power flow model (e.g., forward and backward sweep method) cannot be directly integrated into the optimization models. Instead, Baran and Wu [91] proposed the DistFlow model, which is a viable solution for radial distribution grids. Integrating linearization of the DistFlow model in the restoration optimization is discussed in several studies, for example, Chen *et al*. [27], [61], [62], with verified acceptable accuracy. When load services are being restored, the cold load pickup (CLPU) is a practical issue—a much higher demand than the pre-outage level may happen after an extended outage because of the loss of consumption diversity of a large concentration of thermostatically controlled load. Methods to quantify the CLPU profile are discussed by Schneider *et al*. [92]. Chen *et al.* [61] linearized and integrated a typical delayed exponential CLPU curve with restoration optimization. For the switching operation, the coexistence of both manually controlled switches and remotely controlled switches with different operation times makes the optimization with fixed time steps insufficient. Recent work by Chen *et al.* [63], [65] developed a variable time-step model to handle this condition conveniently, and computation complexity can be largely reduced compared to the traditional fixed time-step model. The interdependency between load restoration and vehicle routing that involves the repair process and mobile energy resource dispatch in the operation stage was studied by Lei *et al.* [52], Chen *et al*. [65], and Arif *et al*. [93], and the benefits of coordinating multiple flexible resources were disclosed.

IV. NMGS FOR IMPROVING GRID ROBUSTNESS AND EFFICIENCY

NMGs can not only boost grid resilience in case of large-scale blackouts caused by both natural and man-made events, but also improve grid robustness and efficiency through seamless coordination of daily operations. Specifically, NMGs can coordinate with each other, as well as with the control center DMS and Distributed Energy Resource Management System (DERMS), to achieve multiple benefits for various stakeholders. In this section, the potential applications of

NMGs for improving grid robustness and efficiency are introduced.

A. Coordination Schemes for Improving Grid Robustness

Grid robustness measures the strength of a system to cope with a given set of disturbances and still maintain its functionality [94]. Grid robustness can be enhanced by harnessing the physical components (e.g., replacing deteriorated transformers, poles, and conductors) such that these components can withstand the more physical impacts of wind, snow, ice, and flood. Moreover, grid robustness can be improved through deployment of advanced control policies for microgrids and controllers, as well as coordination with NMGs in the following aspects:

(1) Enhance the performance of the controllers of generators, DERs, smart inverters, and MGCs to increase system robustness in response to disturbances. Short-circuit and equipment failures are the most commonly encountered disturbances that can cause power outages. NMGs can adopt advanced control and coordination strategies to enhance transient stability performance and enlarge the stability margin (e.g., voltage and transient stability) to withstand disturbances and uncertainties. Shuai *et al.* [95] developed the dynamic equivalent models for DERs and microgrids operated in different modes. The dynamic equivalent models can facilitate the design and operation of NMGs. Li *et al*. [96] presented the formal analysis of NMGs. Amoateng *et al*. [97] introduced an adaptive voltage and frequency control with a PI-free feature to improve dynamic performance. Zamora and Srivastava [98] improved both voltage magnitude and frequency through a multilayer architecture for NMGs. A control strategy introduced by Schneider *et al.* [99] augments the primary frequency response to mitigate the disturbances caused by operating switches and avoids overloading and/or investment in expensive rotating machines. The control of NMGs is discussed in more detail in Section V.

(2) Improve operational flexibility and redundancy by developing alternative energization paths and control solutions. As distributed self-containable entities, NMGs can easily adapt to disturbances in distribution systems by switching between operational modes. In other words, system clustering is a typical solution for improving system robustness based on the concept of NMGs. The clustering problem has been proposed and investigated [100]–[103] considering various aspects such as capacity, location, interconnectivity, and observability and controllability. Bullich-Massagué *et al.* [104] investigated and compared a variety of microgrid clustering architectures considering multiple factors.

B. Coordination Schemes for Improving Grid Efficiency

Coordination between NMGs and the control center can be achieved based on operational objectives, as well as on the architecture and control characteristics of individual microgrids [105]. Lopes *et al*. [106] introduced a new architecture adapted from DMS tools to manage the grid by leveraging the increasing penetration of microgrids. Specifically, some operational applications that can be improved by utilizing NMGs include but are not limited to the following:

(1) Distribution system state estimation (DSSE). NMGs can provide not only measurement data like normal sensors but also estimate load data and model data after processing data locally. Thus, the DSSE algorithm in the control center can assign a higher weight to NMG-processed data and achieve better estimations. Even without centralized DSSE, NMGs can still perform distributed state estimation algorithms. DSSE is detailed in Ahmad *et al*. [107]. For NMGs containing secondary microgrids operated at a low voltage, the state estimation introduced by Bessa *et al.* [108] can be used to achieve real-time state estimation using a subset of smart meters.

(2) Optimal power flow (OPF) and DER management. Similarly, NMGs can be configured as controllable loads or dispatchable power sources to actively coordinate with other resources to further reduce system losses and improve grid efficiency. Furthermore, NMGs can enhance DER integration by compensating for the uncertainties induced by DERs and loads locally, and this can facilitate the modeling and computation requirements for the OPF application in the control center. Arefifar *et al.* [109] introduced a typical energy management process for multimicrogrid systems in which both the operational and economic benefits for coordinating multiple microgrids are justified. Similarly, Karimi and Jadid [110] and Malekpour and Pahwa [111] introduced a stochastic multiobjective framework to optimize the energy management among NMGs coordinated by the control center. Lu *et al*. [112] presented a two-level management approach to coordinate NMGs with hybrid wind turbine-photovoltaic-battery microgrid clusters using a game-based matrix to guide the power exchanges. Du *et al.* [113], [114] leveraged game theory to coordinate NMGs to achieve economic benefits. Parisio *et al.* [115] developed a cooperative model predictive control (MPC)-based approach for each microgrid and coordinated them in a distributed manner. NMG management can also be implemented in a decentralized manner such as the approaches introduced by Feng *et al*. [116], Gao *et al*. [117], and Ma *et al*. [118], as well as in a learning-based manner such as the approach introduced by Zhang *et al.* [119].

(3) Volt and var optimization (VVO) and conservation voltage reduction (CVR). NMGs can be modeled as loads with predictable profiles or controllable power sources in VVO/CVR models, by coordinating resources behind PCCs. Local coordination among NMGs, as well as voltage regulation devices in the field, can achieve regional and system-level voltage regulation, through peer-to-peer communication and distributed control algorithms. In this case, VVO and CVR in the control center can be functionally improved, while the operational complexity can be simplified by assigning voltage regulation set points to NMGs. Many existing works on voltage control using DERs and microgrids can be applied to this application, such as [120], [121]. In Eskandari *et al.* [122] the voltage profiles are regulated by NMGs through a power flow-based voltage estimation approach and a reactive-power sharing approach. In addition, some OPF-based methodologies for NMGs introduced above can be potentially used for solving VVO and CVR problems by adapting the objective functions

and related constraints.

(4) Provision of market services. NMGs can participate in future distribution-level energy markets and coordinate with DSOs to provide the ancillary services operated by an ISO/RTO. For example, NMGs can provide frequency regulation, spinning and nonspinning reserve, demand response, black start, and so on. For example, Chiu *et al*. [123] presents a potential market design, in which multiple operational and economic objectives are quantified as costs. Cintuglu and Mohammed [124] introduced an auction architecture to enable NMGs to participate in the ancillary service market for frequency support. Lin *et al*. [125] introduced a two-level dispatching algorithm for NMGs to participate in an electricity market, with the upper level and the lower level modeled as noncooperative and cooperative game models, respectively. Wang *et al*. [126] introduced a similar two-level framework, in which the DSO optimizes the network topology to cope with the energy-trading activities among multiple microgrids. To meet socioeconomic requirements and implement trustworthy data management, Li *et al*. [127] discussed the application of blockchain technology in NMG energy transactions. While privacy could be a concern for managing NMGs, Hussain *et al*. [128] presented a privacy-preserving strategy for managing NMGs. In addition, NMGs can be coordinated through new market mechanisms, such as the one introduced by Farzin *et al*. [129]. It can be concluded that NMGs can coordinate with the control center, especially DMS, in a variety of operational applications. NMGs can also provide DMS services to local customers in the absence of DMS. The coordination scheme features operational redundancy and flexibility, thus enhancing the robustness and efficiency of the overall system operation.

V. Control Strategies for NMGs

To ensure the stable and resilient operation of NMGs, it is vital to apply advanced controls in individual microgrids and interconnected microgrid clusters. As a holistic and effective control strategy, hierarchical control is proposed and utilized in microgrid operation [18], [130], [131]. It was designed to manage individual microgrids and coordinate the operation of multiple DERs and controllable loads inside each microgrid, evolving from the hierarchical control scheme of the conventional bulk power system, and as a scalable solution, its applicability was further expanded to multiple microgrid clusters, that is, NMGs. In particular, a hierarchical control diagram comprises three levels—: primary control, secondary control, and tertiary control—a design similar to that of legacy power systems with bulk generators. The three control levels are integrated into a cascaded control structure with decreasing control bandwidth from the primary control level to the tertiary control level. In other words, the primary control level is implemented based on local control commands and measurements and commonly based upon droop control, whereas secondary and tertiary control levels are implemented with the assistance of low-bandwidth communication networks. The utilization of low-bandwidth communication networks avoids the potential interferences of secondary and tertiary control levels with local primary control.

For hierarchical control of NMGs, from the control function perspective, the primary control level is principally responsible for local frequency and voltage control in the islanded operation mode or active and reactive power regulation in the grid-connected operation mode. Meanwhile, as each microgrid is controlled as a voltage source in the primary control level, droop control is commonly used to achieve automatic active and reactive power sharing by involving controllable frequency and voltage deviations within the acceptable range. The secondary control level is used to restore frequency and voltage at the critical load infrastructures within the framework of NMGs so that frequency and voltage deviations induced by droop control can be eliminated. Furthermore, the tertiary control level is deployed to respond to the dispatching commands issued by upstream system controllers.

In addition to the basic control functions in the hierarchical control diagram discussed above, advanced control objectives can be achieved by involving an extra degree of freedom with additional control flexibility. In particular, virtual impedance can be deployed in both line-frequency and harmonic-frequency components to enhance system stability and improve power quality (e.g., harmonic compensation, high-frequency resonance mitigation, and so on) [132], [133]. Artificial intelligence techniques (e.g., adaptive neural network) can also be integrated into the hierarchical architecture [97]. In particular, Artificial neutral networks (ANNs) are utilized in the model-based controllers to approximate the model-dependent control dynamics. Therefore, a control diagram that does not rely on model parameters is derived with desired steady and transient control performance. Furthermore, voltage and frequency control loops are proposed to be coupled to improve the primary frequency response of NMGs [99], where adaptive voltage regulators (AVRs) can be activated to adjust the terminal voltage of rotational generators based upon the mismatch between reference and actual frequencies in NMGs. Meanwhile, peer-to-peer control algorithms (e.g., transactive energy control [134]) can be used to enhance the decentralized operation of NMGs. The control functions of the hierarchical control diagram in NMGs are summarized in TABLE III.

TABLE II Functions of Hierarchical Control Diagram in Networked Microgrids

Basic Functions	Advanced Functions
Primary Control Level	
Local microgrid frequency control	Local harmonic compensation
Local microgrid voltage control	Local unbalance compensation
Local active power sharing	High-frequency resonance damping
Local reactive power sharing	Active stabilization
Secondary Control Level	
PCC frequency restoration	Transient process management during system topology change with dynamic microgrids
PCC voltage restoration	PCC harmonic compensation
	PCC unbalance compensation
Tertiary Control Level	
Power flow control	Economic dispatch
Active power exchange	System-level loss minimization
Reactive power exchange	

Note that there are multiple variants of the hierarchical control diagram that can be used in NMGs. Conventional hierarchical control diagrams are implemented by using decentralized primary control levels and centralized secondary and tertiary control levels. However, with local communication among neighboring microgrids, distributed secondary and tertiary control can be implemented, especially with average or pinning consensus algorithms [135], [136], and this is also related to the control diagrams relying on multiagent systems (MAS). Further operational flexibility of NMGs can also be enabled by controllable control diagram reconfiguration, such as switching the role of each controller to mitigate the impacts of system failure [137]. Meanwhile, tie-line converters between each microgrid and distribution substation can be considered in NMGs, and these enable three possible system configurations: islanded microgrids, grid-connected microgrids without tie-line converters, and grid-connected microgrids with tie-line converters [98]. Furthermore, when dynamic microgrids with adjustable boundaries are being considered, transient management during topology change (i.e., during neighboring microgrid disconnection and reconnection) can also be integrated into the secondary control level by involving additional compensation terms [25].

Note that the control diagram of NMGs not only focuses on individual microgrid operation to ensure local frequency and voltage regulation and active reactive power sharing inside every single microgrid but also highlights the interactions between microgrid clusters. In particular, for the hierarchical control diagram of microgrids, NMG control falls into the category of microgrid clusters. Furthermore, when NMGs evolve from conventional microgrids with fixed boundaries to those featuring dynamic boundaries, both steady- and transient-state operational performance should be ensured, and this can also be incorporated into the hierarchical control diagram as additional compensation terms [25], [138].

Given the nature of coupled cyber and physical systems, NMGs are built based on multiple controllable individual microgrids in the physical systems and also communication networks in the cyber layer. The cross-layer architecture requires that the corresponding control diagram be resilient to cyber attacks. This is realized with the improvements of the controller itself and the communication network. Ren *et al.* [139] and Li *et al.* [140] developed an enhanced communication system with a software-defined network (SDN) to achieve resilient NMGs. Abhinav *et al.* [141] developed a resilient synchronization protocol to address sensor and actuator attacks, and attacks on communication networks were mitigated using trust-based controls. Further, Du *et al.* [142] designed a cross-layer configuration to implement dynamic microgrids and incorporate advanced controls in both steady-state and transient processes.

Note that as a comparison between individual microgrids and NMGs, even though there are many aspects in common in terms of control strategies, there are also important control functions that are uniquely designed for NMGs. For example, for dynamic microgrids, implementation relies on smooth topology changes of the concerning distribution feeder, that is, smoothly merging neighboring microgrids and separating single microgrids into smaller pieces. This switching framework was designed as the key feature of dynamic formation of NMGs that requires additional control efforts in the control hierarchy to handle both steady-state and transient processes, as introduced by Wang *et al.* [24] and Hatziargyriou [105]. Furthermore, conventional microgrid control strategies focus mainly on physical circuits to coordinate the operation of multiple DERs for frequency and voltage regulation and active/reactive power sharing. However, for NMGs, they are essentially a cross-layer concept covering both distribution circuits (physical-layer) and communication networks (cyber layer), as clarified by Arefifar *et al.* [109]. These are the main differences between the control strategies for individual microgrids and NMGs.

VI. RELATED RESEARCH TOPICS

A few topics are most relevant to NMGs and need immediate further research. Note that, to enable NMGs, infrastructure is required, including minimum telecommunication with cyber security guarantees and availability of measurement and metering devices. In addition, an enhanced coordination framework with improved optimization algorithms and control strategies is of great importance for the effective integration of NMGs. Other mandatory prerequisites for implementing NMGs include but are not limited to regulatory approvals, tariff schemes, and grid code revisions.

A. *Necessary Infrastructure*

(1) Advanced inverter capabilities. Because most generation sources are inverter-based, advanced control capacities (e.g., frequency-watt droop) are greatly needed to enable the black-start and grid-forming capacities of at least some particular inverters in each microgrid. Such inverters are critically important when a dynamic microgrid is being formed to quickly stabilize the voltage and frequency and balance supply and demand. Research has been performed to create a synthetic system inertia with virtual synchronous machine (VSM) functionalities for inverters. However, such capabilities are not universally available and should be further deployed.

(2) Decentralized controls. Because many existing DER inverters are not equipped with any communication capabilities with ADMS and upper-level controls, decentralized controls with limited or zero communication such as the pinning consensus algorithms discussed in Section V are required. Whereas some black-start-designated DER units may have a certain communication channel with ADMS, universal communication capabilities may not be possible during a large-scale weather event. Control algorithms need to be implemented in order to cope with any unanticipated system conditions to achieve at least functional and suboptimal operating status prior to a full system recovery.

(3) Protective relay coordination. Protective relay coordination is required to accommodate the sometimes unexpected changes of the network topology and power flow patterns. Legacy DER

inverter control settings are very sensitive to disturbances and may lead to unwanted tripping. Some can be reconfigured remotely, while others may demand a hardware update or replacement. More sophisticated ride-through capabilities are important to maintain the available system resources online to the largest extent possible.

B. Enhanced Coordination Framework

(1) Coordination between advanced distribution management systems (ADMS) and NMG controls needs to be in place to address any operational conflicts in normal connection and after-event resynchronization when microgrids are reconnected with the distribution system. Wider hierarchical coordination can also be achieved with bulk transmission grid dispatch signals to local microgrids to attain operating objectives. For example, the bulk power grid may require a microgrid to provide load-shifting capabilities, while the local distribution grid may require the same microgrid to provide local voltage support. Conversely, a local distribution event may have an impact on transmission-level operations as well.

(2) Mobile DER units add the dimension of mobility to the picture. Because mobile units carry sufficient capacity and energy to supply the demand in their vicinity for a short time, the load restoration objective and destination/route selection should be coordinated with a larger system perspective to achieve the maximum load recovered.

(3) From a long-term planning perspective, where and when to place smart switches for network reconfiguration and whether to invest in black-start-capable DERs require a credible simulation and prediction of future system operating status. Other resilience enhancement measurements like those for storage devices, substation elevation, and undergrounding of overhead power lines should also be considered as different alternatives subject to budgetary and technical constraints. An appropriate mix of utility-owned resources and customer-owned assets needs to be maintained in combination with a balance between dispatchable and nondispatchable DERs.

(4) Accurate forecast of DER output and advanced situation awareness (e.g., topology information and device availability) are prerequisites for optimal NMG operations. The associated microgrid controller design should incorporate data analytics abilities that can operate both in the normal operation scenario with large amounts of data streams available and in the emergency restoration scenario in which system observability is degraded, and a quick system fragility assessment and state estimation need to be done to execute any subsequent controls. This capability is particularly important when the boundary of the formed microgrid is changed from the one prescribed before the event.

(5) Uncertainty and variability from onsite DER units and external disturbances are unavoidable. Stochastic programming or robust optimization techniques should be used to capture the variability and uncertainty of nondispatchable generation sources such as PV and wind and possible restoration scenarios when necessary. The derived solutions should be flexible, robust, and predictive.

C. Regulatory Support

Because the interconnection of individual microgrids and the distribution system involves multiple entities with heterogeneous ownerships, mutual agreements and interconnection protocols should be established for energy exchanges in normal and emergent scenarios. Under normal operation conditions, a transactive energy type of market mechanism can enable peer-to-peer energy exchange. Game theoretical approaches are applicable here to achieve equilibrium among various market participants. Communication and control compatibility are also mandatory when the interconnection is necessary for any operation scenarios.

VII. CONCLUSION

In this paper, we survey existing NMGs from fundamental to advanced research topics. We point out that NMGs with fixed/changeable boundaries can be very effective in improving grid resilience, robustness, and efficiency. However, because of their salient departure from the traditional system operation paradigm, many new research topics on NMGs including associated controls, communication, optimization, and market mechanisms emerge. Future research directions to further the development of NMGs are also recommended.

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