Architecture, Control, and Implementation of Networked Microgrids for Future Distribution Systems

Lei Yan, Mehrdad Sheikholeslami, Wenlong Gong, Mohammad Shahidehpour, and Zuyi Li

***Abstract*—Microgrid (MG) is a small-scale, self-sufficient power system that accommodates various distributed energy resources (DERs), controllable loads, and future distribution systems. Networked microgrids (NMGs) are clusters of MGs, which are physically interconnected and functionally coordinated to enhance distribution systems in terms of economics, resilience, and reliability. This paper introduces the architecture and control of NMGs including nanogrid (NG) and MG. To accommodate variable DERs in NMGs, master and distributed control strategies are adopted to manage the high penetration of DERs, where master control focuses on economic operation, while distributed control focuses on reliability and resilience through active power sharing and voltage and frequency regulation. The initial practices of NG, MG, and NMG in the networked Illinois Institute of Technology (IIT) campus microgrid (ICM) and Bronzeville community microgrid (BCM) in the U.S. are presented. The applications of the master and distributed control strategies are illustrated for the networked ICM-BCM to show their benefits to economics, resilience, and reliability.**

***Index Terms*—Networked microgrid, economics, resilience, reliability, master control, distributed control, real-time simulation.**

I. Introduction

CHINA has announced its commitment to reaching carbon peak by 2030 and achieving the carbon neutrality by 2060 [1]. The U.S. also plans to reach carbon neutrality by 2050 [2]. To achieve its "double carbon" goal, it is estimated that China will have 47% of its energy from solar and wind by 2060. Another trend in China's energy transition is the greater percentage of energy which will be in the form of electricity that is set to approach 40% of the total energy consumed by 2030 [3]. Thus, future power systems will have to integrate a high penetration of renewable energy such as solar photovoltaic (PV) and wind, both in centralized and distributed ways but most prominently in the form of distributed energy resources (DERs) in distribution systems, to reduce greenhouse gas emission. It is also envisioned that some modern distribution systems may reach up to 100% penetration of renewable energy [4].

A. Architecture of Future Distribution System

The rapid growth in the utilization of DERs enhances the reliability, resilience, economics, and sustainability of power system. However, high penetration of DERs introduces additional challenges and difficulties in distribution systems as well, e.g., bidirectional power flows, power output uncertainties, and the variety of DERs that would affect the operation and control of power grid [5]. There is an urgent need to find a reliable and secure manner to incorporate high penetration of DERs while enhancing the grid resilience. However, conventional distribution system and energy management solely based on the centralized control inherently lack the scalability and flexibility to coordinate DERs with limited communication resources. Therefore, this paper proposes the physical architecture and coordinated control for future distribution system using a bottom-up approach, as shown in Fig. 1. For the physical architecture, DERs are the basic units to constitute nanogrids (NGs) and microgrids (MGs), and geographically to close MGs from networked microgrids (NMGs). The NGs, MGs, and NMGs can be managed by distribution system operator (DSO) or distributed controller. The DSO, centralized master controller (CMC), and master controller seek their global optimal economical solutions through secure-constrained economic dispatch, whereas distributed controller is a complement to CMC amid NMGs.

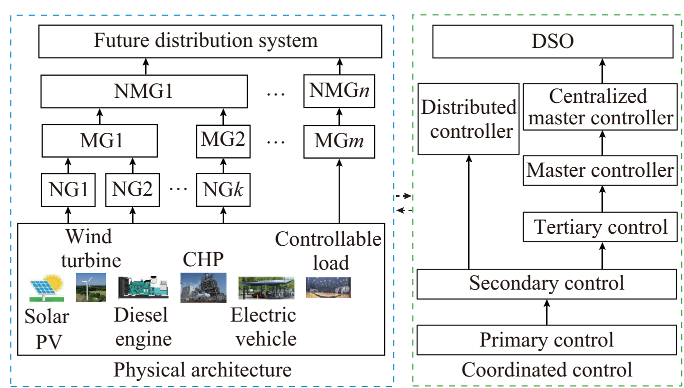

Fig. 1. Physical architecture and coordinated control for future distribution system.

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All controls are based on the hierarchical primary, secondary, and tertiary controls. The primary control features the fastest response to maintain the generation and load balance, but the frequency and voltage may deviate from the rated value. The secondary control aims to restore the rated frequency and voltage while maintaining the power balance. Both primary and secondary controls realize the function of distributed controller without external communication. The tertiary control is to schedule the power resources economically, but it needs to send control signal from CMC to each DER. CMC coordinates the operation of MGs within NMGs.

Overall, the physical architecture and controllers are hierarchical bottom-up systems in the future distribution systems. Each physical layer performs the corresponding operation signal to maintain the power balance and regulate the frequency and voltage, forming a hierarchical and self-controlled system.

MG, an emerging operation paradigm in recent years, provides a promising solution to accommodate variable DERs for delivering reliable, economic, clean, and sustainable energy to customers. MG is defined as a small-scale self-controlled power system, which regulates and manages a group of interconnected DERs and loads within clearly defined boundaries [6]. An MG can connect to or disconnect from the main distribution system to enable it to operate in grid-connected or islanded mode. In case of grid outage, especially under extreme weather condition, MG can operate in islanded mode to continuously support its customers, thus increasing grid reliability and resilience.

NMGs are clusters of neighboring MGs that can be physically interconnected and functionally coordinated to further exploit the potential and benefits of MGs with various DERs [7]. Multiple MGs can be connected to distribution feeders via the points of common coupling (PCCs) and well-coordinated with master or distributed control, which guarantee reliable, economic, and secure operation in grid-connected, islanded, and clustered modes. Under extreme conditions, an MG could deliver the power to other interconnected MGs to ensure the continuous power supply of critical loads and provide other ancillary services for customers.

NG is a much smaller and self-sufficient system with power generation, control, and energy storage, which is quicker and easier to deploy and more affordable [8]. NG can be islanded from distribution system and operate independently during power outages. It is especially important to guarantee the reliable power supply with higher frequency of power outages caused by storms, wildfires, and other extreme conditions even for the U.S. and China in recent years. In addition, NG can be interconnected to a larger-scale grid, e. g., MG, to increase its economic value. Solar PV arrays are always generating the power at times of the day when energy is at the lowest demand in community, but the power can be stored in the utility-owned battery for the backup of peak load times, thus promoting the deployment of solar panels in residential community.

The enabling technology of MG is MG energy management system (mEMS) that will economically manage the MG by intelligently exporting or importing power from the utility grid in the grid-connected mode [9]. mEMS can also request a disconnection from distribution system for the purpose of load shedding or demand response to avoid disruptions caused by distribution system faults or natural disasters. When the breaker at point of interconnection (POI) is open, the mEMS can coordinate the available DERs to supply the power to critical loads. The intelligent and reliable management of mEMS comes from master and distributed controls, which features a hierarchical framework: primary control, secondary control, and tertiary control [10], [11]. Each control has different timescales and different strategies. The faster and device-level controls are usually at a lower hierarchy, whereas slower and system-level controls tend to be at a higher hierarchy. The tertiary control is system-level control that is responsible for day-ahead or real-time economic dispatch. Primary and secondary controls interact with the DERs directly and respond to system dynamics and transients at sub-second level.

B. *Review of Master and Distributed Controls*

The stable and reliable communication between DERs and utility enterprise becomes significantly important through a wide area network (WAN) that provides a control interface for DSO. It ensures the secure and economic operation of MGs in the grid-connected mode. But when the WAN communication fails, it is hard for MGs to regulate the voltage and frequency as well as to balance the generation and loads using master control strategies. It does not have the flexibility and scalability to cope with the emerging DERs as well [12]. The distributed control is capable of functioning as master control to maintain the secure and stable operation of MGs when master control fails to work [13].

The main objective of master control is to minimize the operational cost of MG and maximize its robustness to be immune to unpredicted uncertainties. The uncertainty in renewable energy resources and load impacts the secure and economic operation on any power system, be it large or small. But it is a bigger issue for MG operation as MG has limited flexible resources to deal with unseen difficulties. Scenario-based stochastic optimization and robust optimization are two common methods to address the uncertainty [14]-[24]. Stochastic optimization [14]-[18] generates a large number of scenarios as a proxy to model the uncertainty. However, it is computationally intensive and needs to be further improved [14]. Most studies on robust optimization are two-stage solutions that are for either day-ahead or real-time security constrained unit commitment (SCUC) model [19]-[24]. Most of these models focus on a single timescale with less flexible and less reliable ability than a multi-timescale model. There are mainly two kinds of multi-timescale models. The first one is a two-stage optimization model where the first stage is an hourly dispatch, and the second stage is a sub-hourly dispatch [19]-[22]. References [19] and [21] propose a multi-timescale robust scheduling framework for isolated system with energy storage units. Reference [22] discusses the home EMS with a multi-timescale optimization model. The second kind of multi-timescale models uses two optimization models, where the first model is a day-ahead unit commitment and the second one is a real-time dispatch model [23], [24]. Reference [23] proposes an energy management model that is divided into a day-ahead and intraday model. The day-ahead model determines the baseline transaction, and the intraday model determines the economic dispatch. Different timescale dispatch is considered in [24] for the real-time model. A multi-timescale model for our master controller [25] considers both hourly dispatch and sub-hourly dispatch in the first stage, while the second stage considers the worst case of hourly dispatch.

Generally, NMGs are managed by master controller most of the time. The communication between master controller and DERs of individual MGs ensures the coordinated operation as well as power exchange with utility grid. Fast and reliable communication is essential for data collection, real-time transmission, and processing, but it is relatively vulnerable. Even single-point failure in the communication system may lead to the malfunction of the entire system [26].

Distributed control, which is immune to single-point failure, features higher reliability, scalability, and resilience in the management of MGs [27]-[29]. Distributed control strategies are proposed in [30]-[33] to balance the generation and load while maintaining the voltage and frequency with the communication among DERs. To further reduce the communication burdens, only a small amount of DERs is chosen to access the reference information, which is termed as pinned DERs. In each MG, pinned DERs act as a virtual leader to share the reference information through the internal communication to maintain the normal operation of MGs. The selection of an optimal pinned DER could improve the transient performance in terms of voltage and frequency regulation [31]. Most literature focuses more on individual MG control and communication structures of MGs. However, few studies have paid the emphasis on the control structure of NMGs with specific objectives including proportional power sharing, voltage and frequency regulation, disconnection and reconnection of DERs as well as islanding and reconnection of MGs, etc. The academic community has conducted extensive studies on NGs and MGs. However, the architecture of NMGs and the application of master and distributed control strategies in related practical projects have not been fully reported in the existing literature.

This paper presents the envisioned architecture and control of NMGs, supported by the ongoing practices of campus MG at the Illinois Institute of Technology (IIT) campus microgrid (ICM), the Bronzeville community microgrid (BCM) in the U. S., and the ICM-BCM cluster. To accommodate variable DERs in NMGs, master and distributed control strategies are adopted to manage the high penetration of DERs, where master control emphasizes on economic operation, while distributed control focuses on resilience and reliability through active power sharing and voltage and frequency regulation. Case studies on the application of master and distributed control strategies both in grid-connected and islanded modes are also presented. To lead the development of future distribution system, a number of ongoing research for NGs, MGs, and NMGs and their prospective of being implemented in the networked ICM-BCM are also discussed.

The rest of this paper is organized as follows. Section II presents the architecture of NMGs, and Section III presents the control strategies for NMGs. The ICM-BCM as an example of initial practice of NMGs is presented in Section IV. Section V presents several case studies on the NMG controls. The implementation of several prospective research on NMGs is introduced in Section VI. Section VII concludes this paper.

II. Architecture of NMG

In this section, NG, MG, and NMGs will be discussed in terms of formation, integration scheme, and operation mode as well as the architecture of NMGs. Figure 2 illustrates the architecture of typical NMGs with NGs and MGs by modifying the IEEE 33-bus distribution system. NG is a single component that can be integrated into the MG. The cooperation of multiple participating MGs can prepare for and respond to disruptions in extreme events since it is unlikely for all the participating MGs to be out of service simultaneously. Even in such a worst-case scenario, participating DERs could support NMGs for black start and supply additional power to make the utility grid recover from power outage. MGs are connected to external distribution system to exchange the power in grid-connected mode. In this mode, MGs can import the power from or export the power to distribution system. One MG may have more than two subsystems that are connected to each other with breakers and connected to the distribution system through the transformer. MGs can either directly connect to each other or through distribution system, as shown in Fig. 2. In the case of Fig. 2, MG2 and MG3 are geographically close to each other and can be connected through breakers, but MG1 is far from them and is indirectly connected to them through the distribution system.

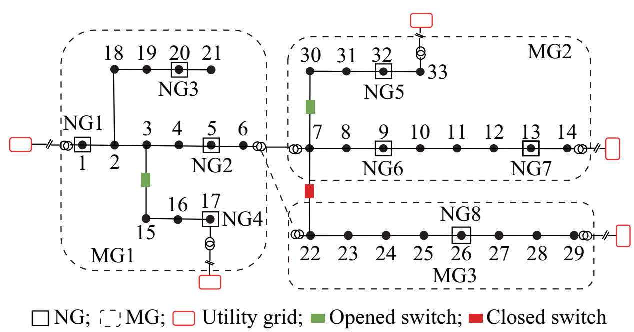

Fig. 2. Illustration of NMGs with NGs and MGs.

A. MG and NG

MG is a small-scale self-sufficient power system that balances local electricity generation and loads which tends to be more economical, reliable, and resilient, especially for the remote rural areas. The deployment of MGs has enormous benefits for both utility grid and local customers. It lowers the electricity price and enhances uninterrupted electricity service with higher power quality for local customers. For utility grid, each MG can be regarded as a controllable aggregated load [34], which provides extra flexibility for demand response in the peak load hours.

NG has a similar structure to an MG, but it is spread out in a much smaller geographic area (e.g., a single building) and usually entails a much smaller capacity [35]. NGs are designed to satisfy very specific objectives, and the implementation of NGs is also subject to fewer technological challenges than those encountered in MGs. In accordance with the increasing popularity of solar-plus-storage utilization at a single-building level, NGs tend to flourish with time.

There is no clear delineation between NG and MG. In practice, the major factor to distinguish NG from MG is its size and power capacity. An NG can be building-level power system, while an MG tends to be larger than an NG and usually serves more than one building. NGs within an MG can supply power to other customers through peer-to-peer (P2P) transaction [36]. More importantly, the integration of NGs enhances the resilience and flexibility of MGs through dynamically adjusting its topology and fixed boundary. Even though the physical boundary of MG is fixed, it can be configured dynamically through adjusting its internal topology thus improving its reliability and resilience for various adversities, where the reliability indicates the system is less likely to the malfunction and the resilience emphasizes more on the system ability to be immune to adversity.

MG provides a well-organized framework to coordinate renewable energy which would be the primary sources of energy to achieve the objective of carbon neutrality by the mid-century. The high penetration of renewable energy would bring significant uncertainty, randomness, and fluctuation to MGs due to their intermittent and volatile nature. To further improve the power supply reliability, multiple MGs could interconnect with each other to increase their power capacity.

DERs in MGs can be classified as grid-forming and grid-following resources. Grid-forming DERs, e. g., natural gas turbines and diesel engines, are dispatchable resources, which provide power sharing to balance power generation and load and regulates voltage and frequency. The non-dispatchable grid-following DERs, e. g., PV panels and wind turbine, are usually operated in maximum power point tracking (MPPT) mode, which can be regarded as negative loads.

B. NMG

Geographically close MGs can be interconnected to form NMGs, which could significantly enhance their reliability and resilience due to the growing power capacity. In recent years, several wide-spread power outages, e. g., blackouts in Texas and California of the U.S., have resulted in huge economic loss and residential inconvenience. NMGs would be operated as an isolated self-sufficient entity that can deliver its continuous power from on-site DERs to critical loads during the extreme events when power supply from utility grid is disrupted. More practical and economical values are that participating MGs can share their cheap and available generation resources to alleviate the power shortage of MGs inside the NMGs, which avoids the power supply interruption.

With close to 100% penetration of electronically interfaced and renewable-based DERs integrated in the NMGs, the system inertia would be reduced, and the variability will be increased that may lead the entire system to the breaking point. NMGs provide a platform for coordinating participating dispatchable resources and dealing with unpredictable operation condition caused by variable DER output and large disturbances. NMGs improve the system reliability, resilience, and flexibility through dynamically extending the boundary of the system from NG or MG to NMGs, which can be changed by operating the associated switchgear and expanding the power capacity of isolated power system. Dynamic boundary allows MG or NMGs to expand or shrink their electrical boundaries by including or excluding part of the MGs or even utility grid. NMGs with dynamic boundary capacity can fully utilize the excessive generation resources of DERs and provides operational redundancy to response to unpredictable conditions.

The deployment of NG, MG, and NMG associated with the abilities to change their internal topologies and external boundaries intelligently and dynamically will make the whole system operate in a reliable, resilient, and flexible manner. The interconnected MGs could coordinate and schedule participating DERs to supply the power for the critical load, e.g., police department, health cares and data center. When they are operated as clustered MGs, one MG is operated in grid-forming mode to regulate its voltage and frequency. The power shortage of one MG will be supplied by other MGs. The selection of grid-forming MG and management of power exchange are under research and deserve carful study [37].

When the NMGs are operated in the grid-connected mode, each MG will be connected with utility grid through respective switches at PCC. As the utility grid usually has adequate power supply, the master controller should schedule the day-ahead and real-time economic dispatch to ensure the MGs operating in economical and reliable manner. Especially, the uncertainty and variability of PV panel output always bring big concern for the reliable and resilient operation of MGs, and master controller should be responsible for this matter. The deployment of NG, MG, and NMGs with dynamic topologies and boundaries provides a promising approach to accommodate emerging and variable DERs, which could be operated in islanded, grid-connected, and clustered modes according to different large disturbances and extreme events. Different control strategies should respond to or manage different operation modes, which coordinate the operation of various DERs, NGs, MGs, and NMGs.

III. Master and Distributed Controls for NMG

MG is envisioned to be a critical part in the future distribution system because of its local intelligence and interoperability as well as the hosting capacity of DERs. The hierarchical collaboration of NG, MG, and NMG could accommodate high penetration of various DERs, which can be operated in grid-connected, islanded, and clustered modes as well as seamless switching between different modes. The deployment of NG, MG, and NMG could contribute to accommodate various DERs but makes it difficult to operate and control in a reliable and resilient manner. The problem can be solved through either master control or distributed control, which includes three control levels: primary, secondary, and tertiary controls.

A. Hierarchical Control: Primary, Secondary, and Tertiary Controls

The primary control directly interacts with the distributed devices in the MGs and responds to the system disturbances and transients. The primary control, as the first level control hierarchy, features the fastest response without the communication with master control and the communication between DERs is kept to a minimum. The common functions of the primary control of MGs include inverter output control and power sharing control. The inverter output control directly manages the voltage and current output of the inverter. It usually implements an outer voltage loop and inner current loop with proportional and integral controller to regulate the voltage and current control. The power sharing control manages the output of individual DERs with their internal communication to keep the generation and load in balance.

As shown in Fig. 3, frequency ω and voltage V decrease after the primary control. $P_{\max}$, $P_{\min}$, $Q_{\max}$, and $Q_{\min}$ are the maximum and minimum active and reactive power, respectively. The secondary control compensates the frequency and voltage deviations by shifting the operating points up to the blue droop curves while maintaining the power outputs P' and reactive power output Q' determined by the primary control. The secondary control ensures the power quality and system stability by regulating the voltage and frequency at rated values, i.e., V_n and ω_n, respectively. The tertiary control is responsible for reliable, secure, and economic operation of MGs in either grid-connected mode or islanded mode. The main objective of tertiary control is to minimize the operating cost of MGs and maximize its reliability. As shown in Fig. 3, the tertiary control will shift the operating points to the setting point, i.e., P^* and Q^*, of economic dispatch while still maintaining the rated frequency and voltage. It will accomplish a variety of energy management functions such as coordinating the operation of multiple DERs, day-ahead and real-time economic dispatch, power quality enhancement, and regulating the power exchange between MGs and utility grid.

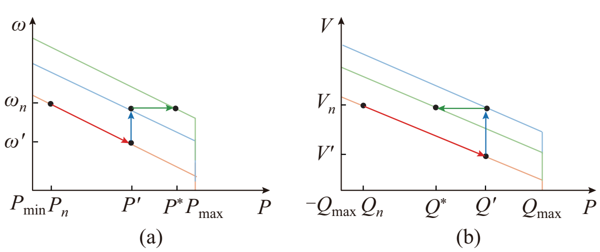

Fig. 3. Hierarchical control: primary, secondary, and tertiary controls. (a) Active power control. (b) Reactive power control.

The hierarchical control strategies are realized through master control and distributed control, as shown in Fig. 4. Each MG has its own master controller to maintain its operation and all the MGs are managed with a CMC that can coordinate all the DERs inside the NMGs and maximize the economic value. The communication requirement of master control is relatively high that each DER should interact with the master controller and each MG needs to communicate with CMC for information exchange. As mentioned above, single-point failure may lead the whole system to malfunction. In case of master control failure, distributed control that is solely based on the local communication through local area network (LAN) can coordinate different DERs and maintain the normal operation of power system. Distributed control is mainly based on primary control and secondary control so that load variations and DER outage will not affect its function.

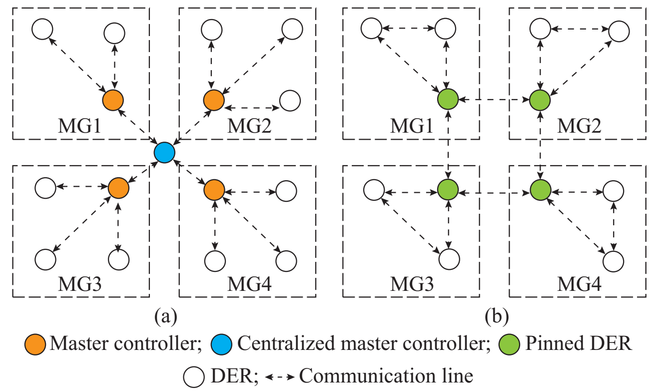

Fig. 4. Hierarchical control strategies. (a) Master control. (b) Distributed control.

B. Master Control Strategy

The uncertainty and variation in renewable energy generation and load consumption always have an impact on the secure operation of any power system, especially a great challenge for MG as it has limited flexible resources to respond to the large disturbances. The design of master control should not only consider the commitment or dispatch cost, but also be immune to the uncertainty and variation.

Energy storage has been implemented on balancing generation and demand, improving power quality, and enabling ancillary services like frequency and voltage regulation. In the existing literature, the battery energy storage system (BESS) is mainly used at the MG level to balance the power generation and demand but not used to mitigate the uncertainty issue of renewable energy such as solar PV unit. The master control can utilize solar PV and BESS in a combined fashion to mitigate the volatility and intermittency of solar PV output in accordance with the prediction. Even if the actual solar PV output deviates from the forecasted values, the master control enables the output of solar-storage system unchanged on an hourly basis. It guarantees the resilience and reliability of MGs even without the support of a thermal unit or utility grid both in grid-connected mode and islanded mode.

As the solar PV unit changes its output within one hour continuously and rapidly, the traditional single-timescale model, e.g., hourly model, can not cope with intermittent disturbance. The application of multi-timescale model can deal with short-term uncertainty and is suitable for real-time application [25]. The compact form of the proposed multi-timescale model is:

$$\min_{(\boldsymbol{P},\boldsymbol{x})\in\Phi} \boldsymbol{C}\left(\boldsymbol{P},\hat{\boldsymbol{P}},\boldsymbol{x}\right) \tag{1}$$

s.t.

$$\boldsymbol{AP}+\boldsymbol{Bx}+\boldsymbol{C}\hat{\boldsymbol{P}}\leq\boldsymbol{b} \tag{2}$$

$$\Phi:=\Big\{\left(\boldsymbol{P},\boldsymbol{x}\right),\exists\hat{\boldsymbol{P}}^{w},\ \boldsymbol{D}_1\hat{\boldsymbol{P}}^{w}+\boldsymbol{D}_2\boldsymbol{P}+\boldsymbol{E}\boldsymbol{\varepsilon}\leq \boldsymbol{h}\ \boldsymbol{F}\hat{\boldsymbol{P}}^{w}+\boldsymbol{GP}+\boldsymbol{Hx}\leq\boldsymbol{g}\Big\}\quad \forall\boldsymbol{\varepsilon}\in\boldsymbol{U} \tag{3}$$

where binary variable vector $\boldsymbol{x}$ represents the commitment variables of base-case condition; $\boldsymbol{P}$ is the dispatch variables of day-ahead dispatch; $\hat{\boldsymbol{P}}$ is the dispatch variables of sub-hourly dispatch; $\hat{\boldsymbol{P}}^{w}$ is the adjusted generation in the worst-case condition due to uncertainty; $\boldsymbol{A}$, $\boldsymbol{B}$, and $\boldsymbol{C}$ are the abstract matrices representing hourly dispatch and sub-hourly dispatch constraints; $\boldsymbol{\varepsilon}$ is the uncertainties; and $\boldsymbol{D}_1$, $\boldsymbol{D}_2$, $\boldsymbol{E}$, $\boldsymbol{F}$, $\boldsymbol{G}$, and $\boldsymbol{H}$ are the abstract matrices of worst-case dispatch constraints. The objective function (1) considers commitment/dispatch cost, exchanged power cost in grid-connected mode, startup and shutdown costs of DERs, load curtailment cost, and regulating reserve cost which is also an important factor to mitigate uncertainties. $\boldsymbol{P}$ and $\hat{\boldsymbol{P}}$ include imported power from the external distribution grid, power exchange of MGs within an NMG and even load curtailment.

Currently, the only practical objective of networking MGs is to export the power from one MG to the other when they are both operating in the islanded mode. In such a scenario, the principles are similar to a bilateral contract. The MG with power deficiency sends a request for assistance, containing the time and amount of power. The MG with surplus power responds with a bid containing the amount of power, time, and price. Finally, the bid can be accepted to reject. However, the future NMGs should not be limited to only power exchange in islanded mode and should be able to engage in wholesale markets for energy, ancillary services, and even arbitrage.

C. Different Operation Modes for DER

Conventionally, generation units in a power system can take a grid-forming role to regulate the frequency and voltage of the system or they can take a grid-following role and follow the active and reactive power setpoints that are provided to them by an external controller or the operator.

For the grid-forming mode, the inputs to the active power control of the generator are the reference frequency and the measured local frequency. The deviation between the two frequencies determines the amount of required active power according to Fig. 3. The inputs of grid-forming mode is illustrated in Fig. 5, where P_{ref} is the reference power, and the value of 60 is the rated frequency. In the grid-following mode, the inputs to the active power control of the generator are the reference active power setpoint and the measured power output of the generator at its terminal. The inputs of grid-following mode is illustrated in Fig. 6, where P_{ref} is the reference power and P_{MACH} is the generator terminal output.

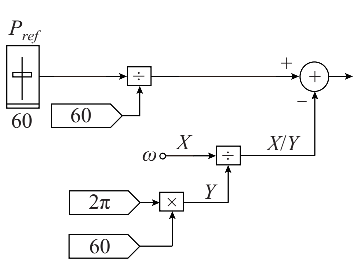

Fig. 5. Inputs of grid-forming mode.

However, for the networked ICM-BCM, there are a set of requirements that makes none of the conventional operation modes viable options. First, each MG is responsible for its own load change, meaning that only the local generator in each MG should respond to the load changes to that MG. This means that the NMG is not one bigger MG formed by the connection of two smaller MGs, with all the assets shared. This is a common, yet unrealistic assumption in the literature. Second, the power on the tie-breaker needs to be controllable, and third, the changes in each MG load should not impact the tie power flow, as long as the physical limits are not reached.

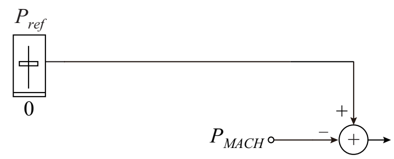

Fig. 6. Inputs of grid-following mode.

Therefore, considering these requirements, a new DER operation scheme is proposed. In the clustered mode, the inputs to the active power control of the generator are the reference and measured power at the point of clustering (POCL). This mechanism has proven to be a viable solution that satisfies all the requirements that has just been explained. Figure 7 illustrates the inputs of the clustered mode, where $P_{ref,POCL}$ is the reference at POCL and P_{POCL} is the measured power at POCL.

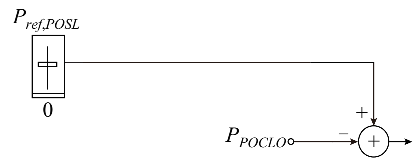

Fig. 7. Inputs of clustered mode.

If an NMG is comprised of two MGs, it should include one grid-forming MG and one grid-following MG. The grid-forming MG will be in charge of frequency and voltage control because it usually has a rotating mass generator to provide the inertia. The designed task of the grid-following MG is to supply the reference power at POCL by adjusting its dispatch. In such a case, with only one POCL, the reference power can be decided by the master controller, and there is no need for a system operator intervention. The two MGS can directly engage in power contracts without sharing any information except the amount of power.

However, in the case of three or more MGs, there is a need for the DSO that has the system-wide information and is capable of running the dispatch and power flow problems at the system level.

D. Distributed Control Strategy

NMGs, with expanded electrical boundaries, could also face more uncertainty and higher chances of large disturbances. The centralized master control strategies might fail to work due to the limited communication and computation capacities as well as single-point failure. The distributed control could function as master control with low communication and computation capacities. In the distributed control, the status of participating DER will be designated as consensus variables which are driven to the desirable values. To reduce the requirement of communication, a small proportion of DERs have direct access to the reference information, and these selective DERs are denoted as pinned DERs that would act as leaders for the remaining DERs to drive their frequencies to the rated values. In the pinning consensus-based distributed control strategy [13], the derivative of frequency setpoint adjustment is:

$$\dot{u}_{\omega i}=-\sum_{j=1}^{n}a_{ij}(\omega_i-\omega_j)-g_i(\omega_i-\omega_0)-\sum_{j=1}^{n}a_{ij}(m_iP_i-m_jP_j) \quad (4)$$

where $a_{ij}>0$ if there is a communication link between DERs i and j, otherwise $a_{ij}=0$; $g_i>0$ if and only if DER i is selected as the pinned DER, otherwise $g_i=0$; ω_0 is the reference value; ω_j is the generator speed of DER j; m_i and m_j are the droop coefficients of DERs i and j, respectively; and P_i and p_j are the active power of DERs i and j, respectively. In this framework, only the pinned DER has access to the reference value ω_0 and has the capability to lead the system to the desirable state. The first two terms in (4) will restore the rated frequency at DERs and the third term in (4) will maintain the proportional active power sharing among participating DERs [13]. Unlike the master controller's objective (economical operation of the system), the objective in this framework is the proportional power sharing among DERs so that all DERs contribute equally with respect to their ratings when supplying the load.

In the theory, pinning one DER is enough to push the system to the desirable trajectory, but the convergency performance might be insufficient to deal with frequency disturbance due to the insufficient number of DERs. Pinning all participating DERs is a waste of communication and control capacity. The selection of pinned DERs can achieve a higher convergency performance if pinned DERs is more effective for the communication with the remaining ones. Pinning DERs with the highest connection degrees could achieve better convergence result [38].

Distributed control is an important complement to the master control, which aims to regulate the voltage and frequency and does not consider the economic operation of NMGs. When the master control fails to work, the distributed control will maintain all the participating DERs at the rated voltage and frequency. The operation of NMGs is mainly based on the primary and secondary controls that drive the operating points to the rated values, as shown in Fig. 3.

IV. Initial Practice of NG, MG, and NMG

A. ICM and its NG

ICM located in Chicago, U. S., is initially referred to as the "IIT Perfect Power System" and later as ICM, a \$14 Million project, which is led by Robert W. Galvin Center for Electricity Innovation. Figure 8 shows the schematic of loop-based ICM that includes seven loops with different color codes and buildings (A-F), and operates at 4.16 kV. Each building name is presented above the building notation. The onsite peak load of ICM is 12 MW with an average value of 8 MW. The total generation capacity of ICM is 12419 kW, including 8000 kW of natural gas turbines, 375 kW of solar generation, 10 kW of wind generation, and 4034 kW of backup generation. ICM also includes a 1500 kWh BESS and several small-size storage devices as well as two 160 kW flywheels. ICM is connected via its two substations to the ComEd utility grid. It can be viewed as an aggregated load to participate in demand response which increases the flexibility of utility grid. In the grid-connected mode, the master controller of ICM could schedule the day-ahead and real-time dispatch through leveraging the power generation of DERs and the power supplied from utility grid. In islanded mode, the master controller could cut some noncritical loads to maintain its operation. When master controller fails to work, distributed controller can work as a backup technology.

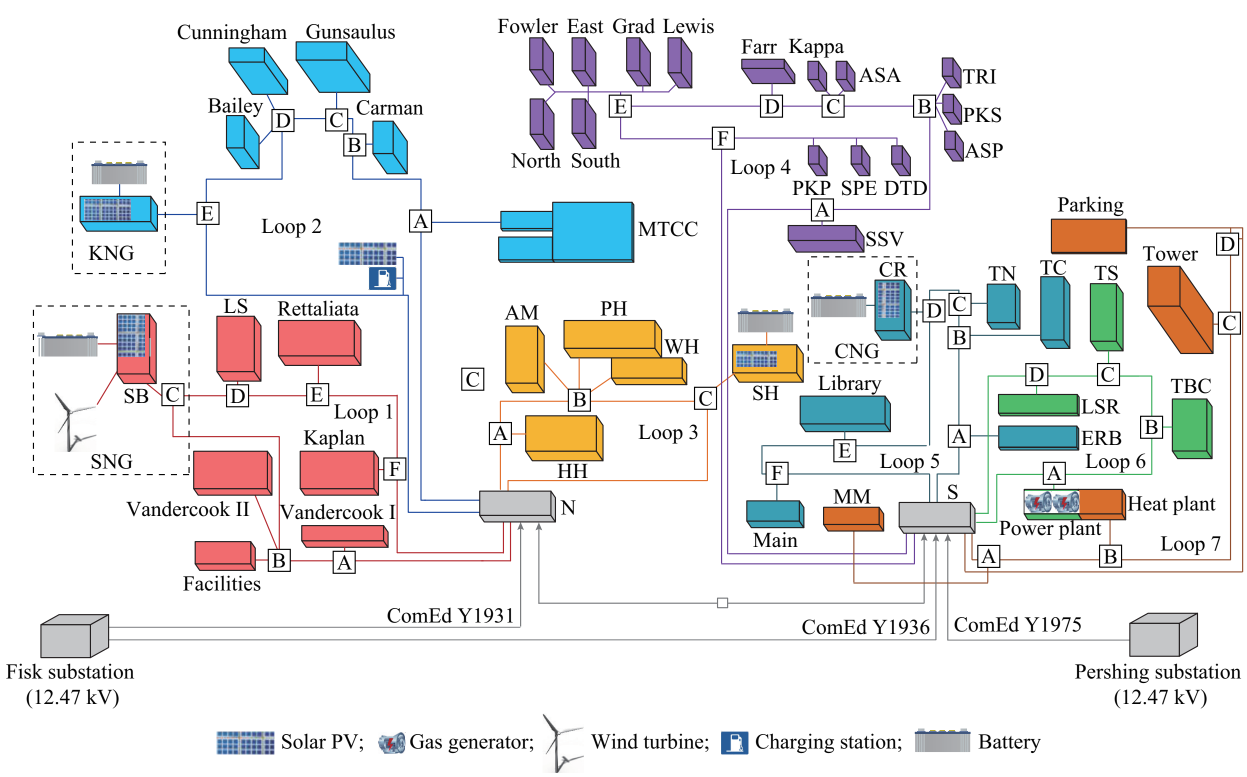

Fig. 8. Schematic of loop-based ICM.

1) Operation Modes and Sequence of Operation

As MGs, NGs, and NMGs are case-dependent, there is a need for the development of detailed and step-by-step instruction that guides the change of operation modes. This detailed instruction is also known as sequence of operation (SOO). SOO needs to be followed step by step if a safe operation of the MG is desired. Figure 9 illustrates the high-level version of the ICM SOO. The light-blue color represents normal operation, light green represents planned change of modes, and pink represents unplanned change of modes. In case of a planned or unplanned outage of one of the two ICM substations, load transfer modes can allow the temporary shift of the loads from one substation to the other by performing a pre-defined operation of breakers. ICM is capable of performing both partial and full islands. For the former, only one substation will be deenergized and ICM will support the loads connected to that substation with local generation. For the latter, both substations will be deenergized, and ICM will locally support its entire load with on-site generators. For clustering, based on the current agreement, both ICM and BCM need to be in the islanded operation mode before they can switch to the clustered mode.

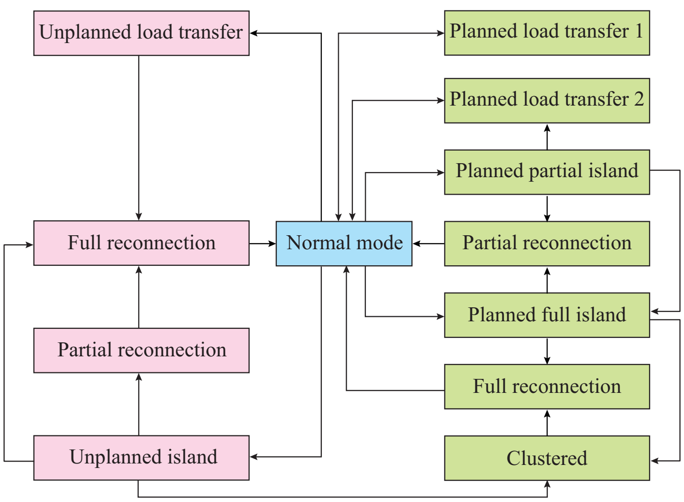

Fig. 9. High-level version of ICM SOO.

Developing a detailed SOO is a challenging task and of importance since going from one operation mode to another cannot be achieved by just flipping a switch. An important detail is often neglected in the literature. Changing the operation modes may involve the change of status of breakers and change of operation mode of DERs. Even the seemingly simplest task such as opening a breaker is a complicated task and involves zeroing out the power flow on that breaker. Also, closing a breaker involves performing synchronization. Furthermore, DERs cannot abruptly change the operation mode as such sudden change might result in system instability.

2) ICM NG

In terms of ICM architecture, it has two layers: the first layer is NG that can leverage abundant space to install DERs like solar PV and BESS; the second layer is MG that is composed of several NGs, as shown in Fig. 8. Both NG and MG are self-controlled power system that greatly improves the flexibility of grid structure and reliability of power supply. ICM features three building-level NGs.

The keating nanogrid (KNG) powering the IIT sports center is located in loop 2 of ICM [35]. Through strategically managing power exchanges, the KNG provides the ICM with additional operational efficiency and flexibility while taking full advantage of on-site generation resources and energy storage devices. The KNG is also able to island itself from the rest of the ICM and continue to function autonomously under emergency conditions so long as the KNG can supply sustained power generation to its critical loads. KNG includes 180 kW solar PV panels, 165 kW/330 kWh energy storage system, and 20 kW controllable lighting system that can be either self-sufficiently operated in islanded mode or supply its generated power to other loops/buildings. Figure 10 shows the hybrid AC/DC architecture for KNG. KNG is a hybrid of AC and DC distribution system. Two sets of rooftop solar PV arrays are connected to AC and DC subsystems separately. Batteries that store DC power are utilized in each subsystem to level off the variability in the output power of PV arrays. AC loads, e.g., swimming pool pump, and DC loads, e.g., light-emitting diode lighting, are included in the respective AC and DC subsystems. The AC subsystem is connected to the rest of the ICM, allowing the KNG to exchange the power with the ICM when there is a power imbalance in the NG. The AC and DC buses are interlinked through bidirectional AC-DC converters that can transfer the power between the two subsystems and regulate bus voltage magnitudes. In case of a campus power emergency, the KNG can be islanded from the rest of the ICM and operated as a standalone power system.

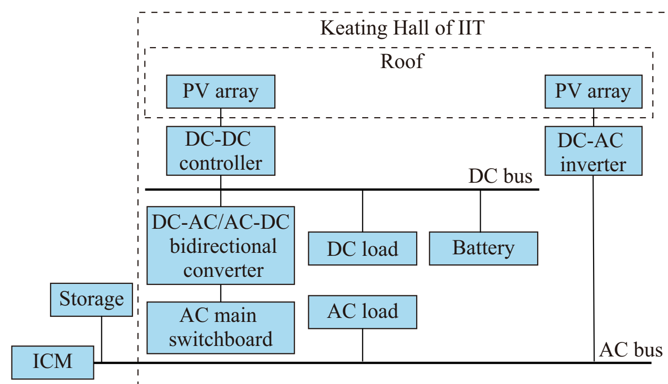

Fig. 10. Hybrid AC/DC architecture for KNG.

Located in loop 5 of ICM, crown nanogrid (CNG) powers Crown Hall, a U.S. National Historic Landmark [39]. The introduction of renewable energy and energy storage technologies to this building have elevated its stature as an energy efficient landmark in the city of Chicago, U.S.. CNG includes a 75 kW solar PV system and a 300 kW/500 kWh Tesla BESS. The PV and BESS, together with their associated control relays, software, and modifications to the building's distribution system, making Crown Hall a stand-alone NG. With an average load of 60 kW, CNG could also deliver its surplus power to other critical loads of ICM. The BESS will charge and discharge on a daily basis. To optimize the utility and cost savings, the BESS controller is programmed to maximize the power reduction while still fully recharging prior to the demand window the next day. This is done by setting the minimum demand response power setting to still enable full recharge during the "off hours". Modeling a 48-hour period, Fig. 11 shows the BESS operation in CNG without PV discharge window. Note that this scenario does not include the benefit of the solar PV system (assuming worst-case cloudy conditions). The "daily demand-response window" refers to the scheduled demand response time by the utility grid.

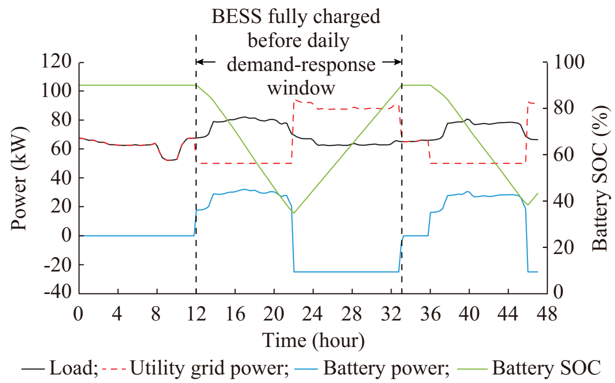

Fig. 11. BESS operation in CNG without PV.

Located in loop 1 of ICM, the Stuart nanogrid (SNG) powers the IIT data center. SNG includes 100 kW solar PV panels, 10 kW wind turbine, a 300 kW/500kWh BESS, and a 500 kW backup diesel generator.

B. Networked ICM-BCM

The BCM project led by the Commonwealth Edison (ComEd) company aims at providing residents and critical facilities with sustainable and innovative power services [33]. There are two 12.47 kV subsystem in BCM. The operation of BCM is managed by MG management system (MGMS). BCM is geographically adjacent to ICM, and there are several breakers connecting the two MGs.

1) ICM-BCM Cluster

The schematic of networked ICM-BCM is shown in Fig. 12, which includes various types of DERs, including combined heat power (CHP), wind turbine, PV panels as well as BESS units. It should be mentioned that this figure only represents the relative location of major system components, including substations, DERs, and loads and does not represent the actual topology of the system, including the loop structure of ICM. For ICM, it has seven loops, which are interconnected physically and can also be electrically linked to each other in case of power outage. For BCM, it has two subsystems and all the DERs are in the second subsystem. In the grid-connected mode, they absorb power energy from utility grid. When they fail to connect to utility grid, DERs in the second subsystem will be dispatched to supply the power to the first subsystem.

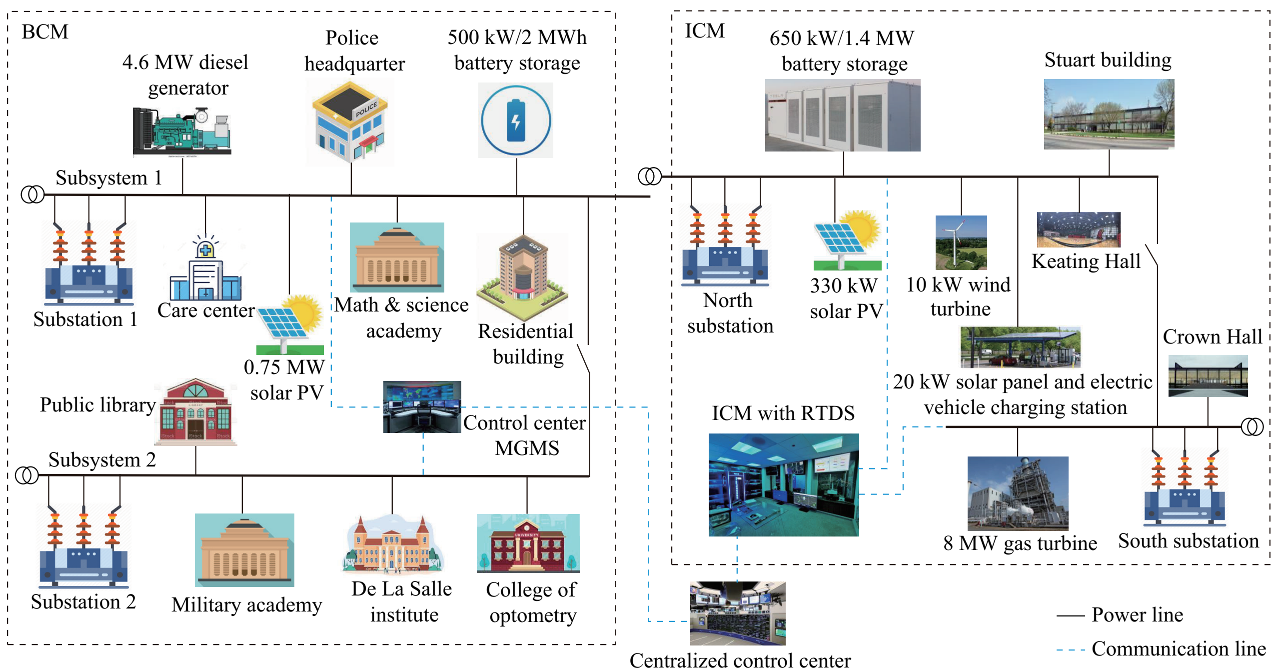

Fig. 12. Schematic of networked ICM-BCM.

2) Clustering or De-clustering Procedure

For the clustered ICM-BCM, one of the two scenarios can take place. First, the islanded BCM has less generation than its forecasted load. In such a case, BCM will let ICM know the amount of power it needs, which should respect the amount of surplus at ICM. The other scenario is the opposite case, meaning that the islanded BCM has surplus generation and will let ICM know in case it needs to request the power.

The clustering and de-clustering procedures should follow the SOO. This procedure has two levels: transaction level and operation level. These levels can be observed in Fig. 13. At the transaction level, the master controller of the two MGs will communicate with each other to settle on the time range, amount of power, and price. For the first scenario in which BCM has power deficiency, the transaction level steps are as follows. First, a request for assistance will be sent from BCM to ICM containing the required power and amount of time. Upon receiving the request, ICM will reply by sending an offer for assistance, which contains the price and the amount of the power it can guarantee for that time period. Finally, BCM will let ICM know if the offer is accepted.

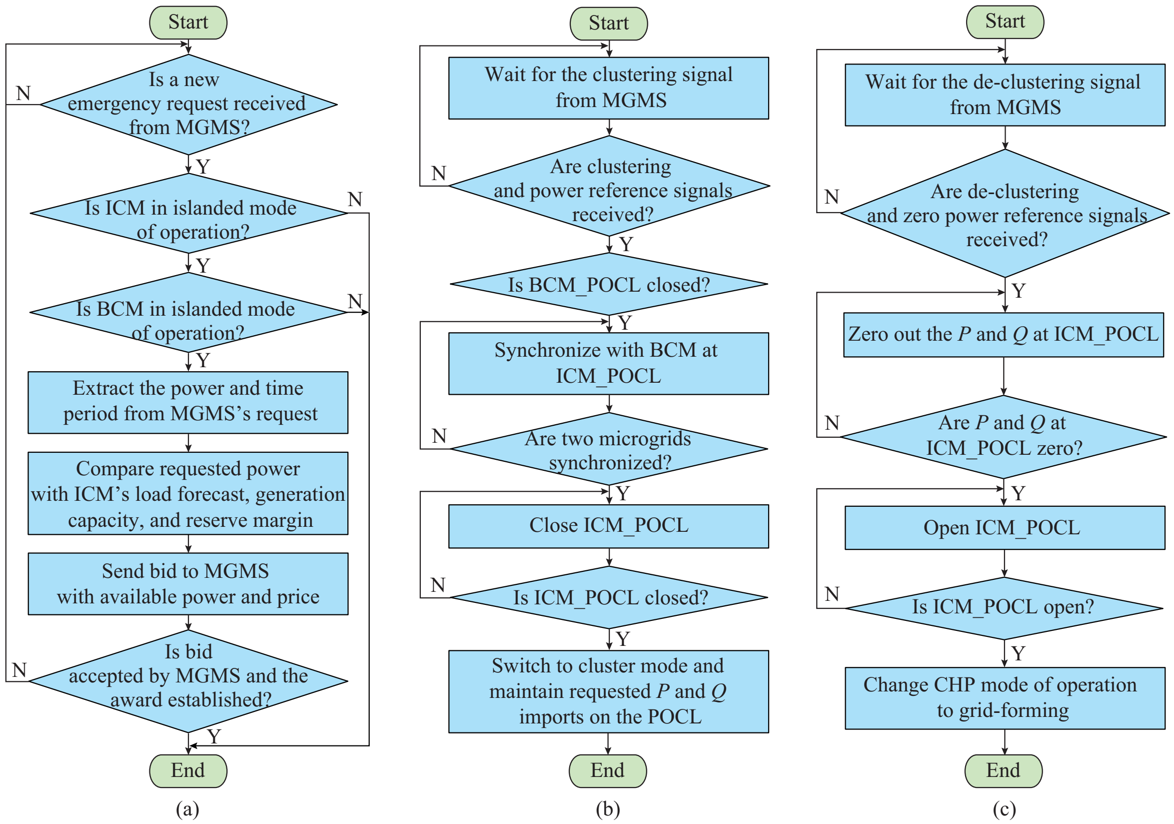

Fig. 13. SOO for clustering and de-clustering procedure. (a) Transaction level: web services. (b) Operation level: cluster. (c) Operation level: de-clustering.

The operation level ensures that the settled agreement on the transaction level is properly executed. For clustering, first, it must be ensured that both MGs are in the islanded mode. Then, the normally-open breakers between the two MGs, also known as ICM_POCL for ICM side and BCM_POCL for BCM side, need to be closed after the synchronization is performed. Finally, the ICM generator should switch to the clustered mode and maintain the agreed amount of power on the tie breaker between the two MGs. Finally, for de-clustering, the first step is to zero out the power flow on the tie breaker. Then the POCL breakers can be opened, and the two MGs should change their operation mode back to islanded mode.

V. Case Study on Master and Distributed Controls

The deployment of NMGs provides a platform to accommodate variable DERs and mitigate their effects of variation and uncertainty, which can be viewed as an aggregated load to participate in the distribution system operation, especially for load curtailment and demand response. With master and distributed controls, MGs can maintain the power balance, and regulate frequency and voltage, which are operated in an economic, reliable, and resilient manner. In this section, the MATLAB and real-time digital simulator (RTDS) will be used to demonstrate the effectiveness of the master and distributed control strategies.

A. *MG as an Aggregated Load*

Since the beginning of September 2021, load curtailment and forced cuts to industrial fields and residential community in China have been widening amid electricity supply issues and a push to enforce carbon emission regulations. The record high coal prices are making it unprofitable for many coal-fired power plants to operate. The state of California faces the largest power outage in its history caused by a heatwave in August 2020 and the state of Texas suffered a major power crisis as a result of winter storms in February 2021. The gross imbalance of power generation and demand leads the power system to catastrophe, which demonstrates that conventional power supply is hard to deal with extreme events such as heatwave, storms, and even economic crisis.

The emerging NG, MG, and NMG can be regarded as an aggregated load (either positive or negative) to support the proper functioning of utility grid with their flexible generation resources and manageable loads in peak hours. Figure 14 shows the demand response of ICM to actively reduce load during peak hours, which is a real case of ICM responding to the utility grid command during peak hour on July 16th of 2021 through dispatching CHP and BESS. ICM with 8 MW CHP, 330 kW PV, and 650 kW BESS capacity is perfectly capable of supplying power demand of IIT campus. ICM also could deliver surplus power to neighboring BCM to supply power deficits through regulating the switch connecting ICM and BCM, if the power generation of BCM is less than its load in islanded mode.

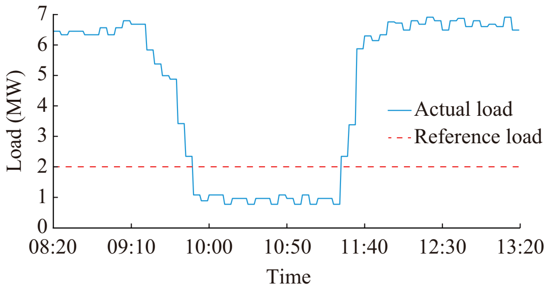

Fig. 14. Demand response of ICM to actively reduce load during peak hours.

B. Enhancing Economics with Master Control

Compared with a single-timescale model, the proposed master control strategy uses a multi-timescale model, which demonstrates how a model with different timescales highly affects real-time dispatch, the costs of BESS units, thermal units, and exchanged power in grid-connected mode or load shedding in islanded mode for real-time dispatch.

A criterion for comparing the multi-timescale model and single-timescale model is their optimality in terms of the total costs. The corresponding results will be applied to real-time dispatch. Note that the real-time dispatch is sub-hourly model and the solar PV and load profiles in real-time dispatch are identical to those of multi-timescale model. Table I shows the comparison between multi-timescale model and single-timescale model during 7 a.m. to 18 p.m.. As solar PV unit generates non-zero power during 7 a.m. to 18 p.m., such time periods will be chosen for the real-time dispatch tests. In grid-connected mode, there is no notable difference between the two models since the BESS unit is used to track the changing output of the solar PV unit in real-time dispatch. However, it is not the case in islanded mode. The cost of thermal units for single-timescale model is \$11279.04 while that for multi-timescale model is \$8303.76, and the difference is \$2975.28 (35.83%). There is no load shedding cost when the unit commitment and regulating reserve of multi-timescale model are applied but the load shedding cost is \$1066.91 for single-timescale model. As can be observed in this test, the proposed master controller is more economical in islanded mode than those of single-timescale model. Moreover, the master controller is also "load-friendly" and reliable because no customers suffer from power outage.

C. Enhancing Resilience/Reliability with Distributed Control

The superiority of distributed control in terms of reliability and resilience mainly results from the flexibility of controllable DERs and intelligent control algorithm. Resilience focuses more on the system ability to mitigate or recover from adversity and reliability emphasizes on normal operation of MGs in case of DER failure. Different MGs have various DERs and loads, so without the loss of generality, two interconnected MGs are applied to demonstrate the function of distributed control. Both the first MG with three 200 kW generators and four loads and the second MG with two 200 kW generators and two loads are connected to a distributed system.

TABLE I
COMPARISON BETWEEN MULTI-TIMESCALE MODEL AND SINGLE-TIMESCALE MODEL DURING 7 A.M. TO 18 P.M.

Cost terms of real-time dispatch	Grid-conned mode		Islanded mode	
	Multi-timescale (\$)	Single-timescale (\$)	Multi-timescale (\$)	Single-timescale (\$)
BESS unit	10.23	10.23	10.23	10.23
Thermal unit	6868.78	6931.22	8303.76	11279.04
Exchanged power	813.58	732.49	0	0
Load shedding	0	0	0	1066.91

1) Resilience of NMG with Variable Load

As NMGs are a small-scale power system, the load variation easily leads to high-voltage and high-frequency fluctuations and even causes systemic malfunction. As mentioned above, resilience refers to the system ability to recover from unpredicted adversity such as load variety. Figure 15 shows the performance of the proposed distributed control with varible load at $t=1.2$ s; the second load decreases from 80 kW to 50 kW at $t=7.2$ s, and recovers to 80 kW. It can be observed that the frequency can reach steady state in about 4 s.

When the load changes, participating DERs will proportionally share their power output to mitigate the NMG imbalance. The frequency of each DER increases or decreases immediately based on the primary control. Then the proposed distributed control strategies will gradually restore the frequency to the rated value based on the secondary control while maintaining the proportional active power sharing, as shown in Fig. 15. The convergency rate mainly depends on the network structure of NMGs and communication speed.

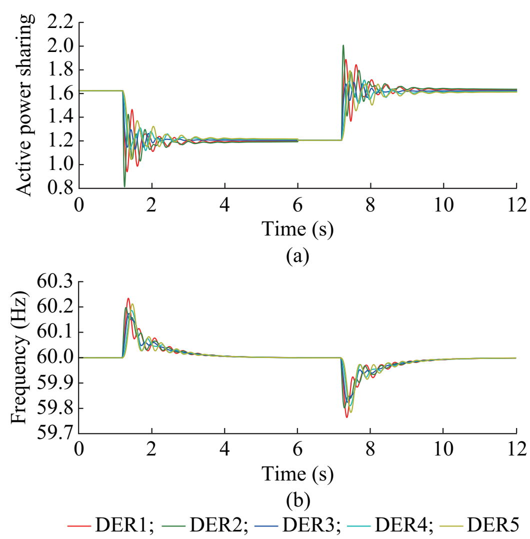

Fig. 15. Performance of proposed distributed control with variable loads. (a) Active power sharing. (b) Frequency.

Even though the NMGs are not operating according to the economic dispatch, the coordination of DERs and local communication networks ensures its resilience and security. For the small-scale power system, some heavy loads have a major impact on the stability of NMGs, especially in islanded mode. The power balance and frequency regulation ensure the normal operation of islanded NMGs.

2) Reliability of NMGs with DER Disconnection/Reconnection

DERs in NGMs tend to have more chances to disconnect from and reconnect to the distribution system because of its failure and maintenance. Figure 16 shows the performance of the proposed distributed control with DER disconnection and reconnection. At $t=1.2$ s, DER1 disconnects from the system, and it reconnects to the distribution system at $t=7.2$ s.

When the disconnection happens, DER1 is no longer available for the NMGs, and its power output decreases to zero immediately. Other DERs will work together to share the active power proportionally. Because the power supply is less than the demand, the frequency will decrease immediately based on the primary control, then it gradually recovers to the rated values in about 4 s as well. It can be observed that in case of DER failure, the system will be back to normal status after a short time of adjustment with distributed control. The recovery process highly depends on the DERs' capacity and the local communication among DERs. For example, the convergence rate is associated with the communication of different DERs and the selection of pinned DERs. When the power supply is less than power demand, the strategic load curtailment will be implemented according to the priority sequence of different loads.

VI. Implementation of Prospective Research on NMG

The smart grid program in the U. S. since 2007 aims to modernize the nation's power system and recover from economic crisis. These efforts are critical to achieve the nation's ambitions for renewable energy development, electric vehicle adoption, and energy efficiency improvements. The extensive MG development will create a more resilient, sustainable local community. Aside from the ICM which represents the physical layer, the IIT real-time digital simulation (IRTDS) lab has enabled researchers to lead the research of NMGs on the cyber layer as well. It should be noted that real-time simulation and the digital twin studies are very important for the implementation of MGs and NMGs as they are new developments. A number of state-of-the-art research works are under way such as the blockchain-enabled electricity transaction and reconfigurable operation of networked building MGs. Such research works have to be extensively tested before they can be implemented in the field for the ICM-BCM cluster.

A. RTDS Model of Networked ICM-BCM

Before the deployment of the networked ICM-BCM in the field, it was necessary to develop the RTDS model and conduct extensive tests. This task is performed in three major steps. In the first two steps, each MG model is individually developed and in the third step, a power exchange mechanism is developed for interconnecting the two MGs. The most current model of this NMG occupies two RTDS NovaCor racks and uses the total of 598 electrical nodes, out of the available 600 nodes. For each MG, in islanded operation mode, the natural gas turbines will become grid-formers and other available DERs will be grid-followers. In the networked form, The BCM's generator will operate in the grid-forming mode to maintain the system frequency and voltage, and the ICM generator will perform in clustered mode to regulate the exchanged power between the two MGs. For the PV and batteries, generic average models are used to save computational resources, as it is a major challenge in the development of RTDS model. Furthermore, this model is developed in 50-μs time step. Since its development, this model has been involved in several government and industry funded projects and three of them are introduced as follows.

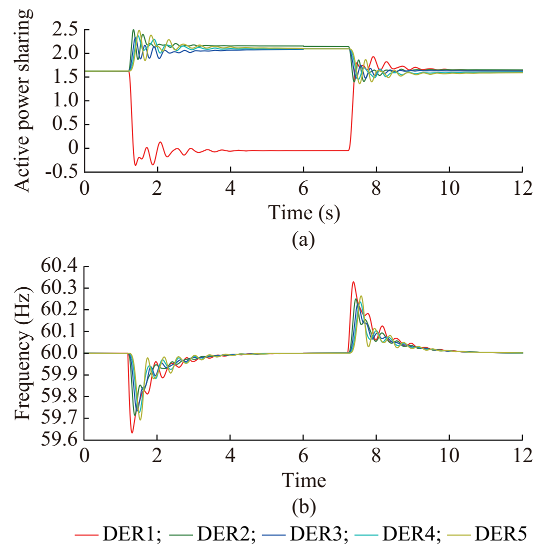

Fig. 16. Performance of proposed distributed control with DER disconnection and reconnection. (a) Active power sharing. (b) Frequency.

B. Blockchain-enabled Energy Marketplace

The aim of this research project is to address the issue of cybersecurity by demonstrating the performance of blockchain in NMGs. A two-level architecture for MG transactive energy management between two adjacent MGs is considered. The RTDS model of the networked ICM-BCM is chosen as the testbed for this study. At the first level of the architecture, each MG individually manages its local DERs and load. The developed program in charge of such asset management is referred to as clearing engine. At the second level of the architecture, the DSO has the responsibility of managing the grid; and if necessary, reconfiguring the power distribution network for enhancing the local network security; and facilitating the peer-to-peer energy trading among NMGs [40]. The security that is provided from this blockchain covers a range of services and the most important ones are related to tamper-proofing and digital finger printing of data for authentication.

C. Reconfigurable and Resilient Operation of Network-controlled Building MGs with Solar Integration

The focus of the research project is the coordinated operation of multiple building MGs to increase the resiliency, especially when they are operating in islanded mode. For this purpose, a bi-level reconfigurable framework is employed. For the first level, each building MG and its assets including solar PV sources, BESS, and dispatchable generators will be coordinated to stabilize local frequency and voltage in islanded mode. At the second level, adjacent building MGs can be merged dynamically based on topology reconfiguration to share their assets collectively [41]. A modified version of the ICM RTDS model is used for the lab testing of this project.

D. Digital Twin of ICM

With both the real-time simulator as the digital layer and the actual ICM-BCM NMG as the physical layer, great opportunities of bridging the gap are provided between the two layers by developing a digital twin, which is digital model that accurately represents a physical product. They have recently gained a lot of attention in the academia as well as the industry for their promising capabilities in closing the engineering loop. Having a digital twin will allow researchers to claim with the confidence that the digital model fully represents the physical model. This will allow researchers to perform the research and development on the digital side to evaluate the impact of any change before performing it on the physical system.

VII. Conclusion

This paper introduces the fundamentals and operation modes of NG, MG, and NMG as well as the architecture of NMGs for future distribution systems featuring high penetration of DERs. Initial practices of NG, MG, and NMG in the networked ICM-BCM demonstrate that NMGs are critical for the future distribution system. To better manage the MG and NMG in terms of economics, resilience and reliability, this paper also illustrates the details of master and distributed control strategies to coordinate various DERs. Master control could improve the economical values of MGs and distributed control could ensure the normal operation of MG and NMG through regulating the voltage and frequency even without the communication to master controllers.

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