Exploring the Possibilities of the IIT-Bronzeville Grid

BRONZEVILLE IS A COMMUNITY located in the city of Chicago that features a diverse historic district with essential city services, residential housing, and educational institutions. The Bronzeville neighborhood houses the headquarters of the Chicago Police and Fire Department, De La Salle Institute, Illinois College of Optometry, Boulevard Care Center, Chicago Public Library, Pilgrim Baptist Church, Bronzeville Nursing and Living Center, Chicago Military Academy, Pentecostal Church, Perspectives Math & Science Academy, and other institutions. The area provides an ideal location for the continued refinement and development of advanced electric power services, which can be demonstrated through the implementation of a community microgrid: the Bronzeville community microgrid (BCM). The BCM is the backbone of a planned community of the future, where residents and critical facilities enjoy a sustainable environment and utilize innovative smart grid products. The BCM can serve as a pilot project for demonstrating the merits of instituting Chicago as a smart city. Distribution automation devices capable of fault interruption and

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Networked Microgrids

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sectionalization will be strategically deployed so that a fault would only result in a local outage rather than an interruption to the entire area. The BCM operation will comprise several types of distributed energy resources (DERs). A battery energy storage system (BESS) located in close proximity to photovoltaic panels provides an effective means to mitigate the variability of renewable energy. The BESS is also effective in improving the power quality at customer sites.

The BCM is adjacent to an existing microgrid on the campus of the Illinois Institute of Technology (IIT), which owns, manages, and operates its electric distribution system. The IIT campus microgrid (ICM) is bounded by 35th Street on the south, 29th/30th Street on the north, Michigan Avenue on the east, and the Metra Rock Island train line on the west. The on-site 12-MW DERs located at the ICM include dispatchable units such as a natural-gas turbine and a BESS as well as nondispatchable units such as photovoltaic panels and wind turbines. The ICM features seven separate loops for enabling a high-reliability electric distribution system, which originates from two substations; three loops are connected to the north substation, and four loops are connected to the south substation. Figure 1 shows the ICM's seven loops, with each loop represented by a specific color.

An ongoing funded project, sponsored by the Office of Electricity Delivery and Energy Reliability at the U.S. Department of Energy, aims at devising a master controller for achieving a seamless integration of the BCM and ICM as networked microgrids to broaden the merits of microgrid-based distributed power systems. The project team led by Commonwealth Edison comprises multiple universities, national laboratories, consultants, and industrial manufacturers. Through strategic sharing and control of available resources in the two

figure 1. The seven loops at the IIT campus microgrid.

microgrids, the proposed networked microgrids are expected to further reduce the outage time of critical loads at lower costs, improve the overall grid operation, enhance the grid efficiency, and reduce the local emissions in the Chicago community.

We present the strategies and benefits of networking multimicrogrids by prototyping the planned IIT-Bronzeville networked microgrids. In practice, networked microgrids can improve the efficiency, security, sustainability, reliability, resilience, and economics of the electric power supplied to end customers. We introduce the ongoing efforts for connecting the planned BCM to the existing ICM to form networked microgrids. We propose coordinated control strategies for overcoming the technical difficulties in operating the networked microgrids when they are islanded from the utility grid and discuss the significant role of networked microgrids in realizing a smart grid.

Benefits of Implementing Microgrids

A microgrid is a localized small-scale power system that clusters and manages DERs and loads within a defined electrical boundary. Through the strategic control of switchgear located at the point of common coupling (PCC), each microgrid can be operated in either grid-connected (when connected to the utility grid) or islanded (when disconnected from the utility grid) mode. Microgrids take advantage of locally available resources and thus could reduce their dependence on the utility grid to serve on-site customers, in particular when critical circumstances are encountered. By interacting actively with the utility grid, microgrids are also capable of supplying surplus energy and auxiliary services (e.g., frequency regulation, voltage support, spinning reserve, black start support, and economic and emergency demand response) to the utility grid. Microgrids may vary in functional designs by considering the unique characteristics of individual power supplies and demands. Although ac microgrids are dominant in present electric distribution systems, dc microgrids and hybrid ac/dc microgrids are becoming increasingly prevalent due to the proliferation of photovoltaic power generation and dc loads (e.g., computers, mobile phones, and light-emitting diode lighting). Microgrids may evolve to become the fundamental building blocks of a smart grid. The emergence of microgrids spurs interest for exploiting the benefits of DERs through the utilization of advanced management and control strategies. Moreover, the needs for enhancing energy efficiency, economics, security, sustainability, reliability, and resilience drive microgrids within a region to form networked microgrids.

Driving Forces for Networking Microgrids

Geographically close microgrids can be interconnected to form networked microgrids. These microgrids are collectively viewed by the utility grid as an aggregated and controllable entity that can support the objectives of the local utility for serving individual loads in their service territory. If implemented and managed properly, networked microgrids can introduce a variety of benefits to electric power utilities and consumers. Their deployment provides a new paradigm for the operation and the management of electric distribution systems with a high penetration of DERs. Such networked microgrids can offer additional operational flexibility for realizing the benefits of variable DERs more effectively. The networked microgrids act as a credible means of reducing the installed generation capacity by sharing available resources in individual microgrids, which can significantly improve their effectiveness.

Networking a series of autonomous microgrids is a strategic effort toward delivering a high-quality and environmentally friendly supply of power to local customers by taking full advantage of DERs shared by networked microgrids. In addition, the economic allocation of electric energy resources to loads can be optimized more comprehensively. Accordingly, energy management decisions tend to arrive at the global optimum for networked microgrids rather than achieve a local optimum for individual ones. It is also important to note that networking microgrids boost the reliability and resilience of power services in the associated microgrid regions. Accordingly, each microgrid can provide backup power generation to others to maintain the regional power balance without interrupting energy supplies to critical loads. In essence, the deployment of networked microgrids provides a platform for aggregating power services potentially offered by individual microgrids for small-scale DERs to participate more actively in electricity market decisions (e.g., the day-ahead wholesale market).

Such cooperation among networked microgrids helps local power services adapt to changing conditions in the wake of disruptive events in a cluster of networked microgrids. The networked microgrids bestow more opportunities to respond to, and recover from, disruptions in extreme events since the probability that multiple microgrids fail simultaneously is low. Networked microgrids can also supply their surplus energy to facilitate local power restorations in external areas managed by local power companies. Accordingly, regional resources are expected to benefit from the interconnection of microgrids by increased reliability that can be measured by common reliability indices such as the System Average Interruption Frequency Index and the System Average Interruption Duration Index.

Implementation of the IIT-Bronzeville Networked Microgrids

To explore the possibility and benefits of networking multi-microgrids, two adjacent microgrids (i.e., the ICM and BCM shown in Figure 2) will be physically tied together. The ICM and BCM have separate PCCs for their connections with the utility grid (i.e., S1 and S2 for the ICM and BCM, respectively, shown in Figure 2). Disconnecting the PCC switches will result in islanded networked microgrids. In Figure 2, the ICM and BCM are tied directly by a fully controllable interlinking converter (IC) that is in parallel with distribution feeders and enables bidirectional power flows between the two networked microgrids. The S3 switch is a normally open switch, as the IC provides a buffer between the two microgrids, which have distinct operational requirements, so that they can be operated as two independent and autonomous entities both connected to the utility grid. If the microgrid frequencies are the same, the IC in Figure 2 can be considered as a simple tie-line for linking the two microgrids. The proposed design of networked microgrids with the IC not only provides additional opportunities to enhance regional reliability and resiliency but also eases the control strategies for achieving better energy efficiency, economics, and sustainability.

A master controller (MC) is deployed in each microgrid and is capable of communicating with the other microgrid MCs through a low-bandwidth communication channel. As a central source of communication, coordination, and management of loads and generation resources, each MC continuously monitors a microgrid's operating conditions (e.g., frequency and voltages) and periodically performs optimal energy management to utilize the available resources for load balancing in an efficient and secure fashion. The OSIsoft PI system is employed in Figure 2 as a middleware to help each MC achieve its operation and control objectives. The OSIsoft PI system serves as a universal system that synchronizes and integrates the real-time information pertaining to diverse sources of data (e.g., DERs, phasor measurement units, and building meters) across the microgrid, regardless of communication protocols, while performing data analyses and visualization to guide the MCs to make operational decisions more efficiently.

Figure 3 shows the data flow for realizing the MC functionalities. The data flow hierarchy can be divided into three

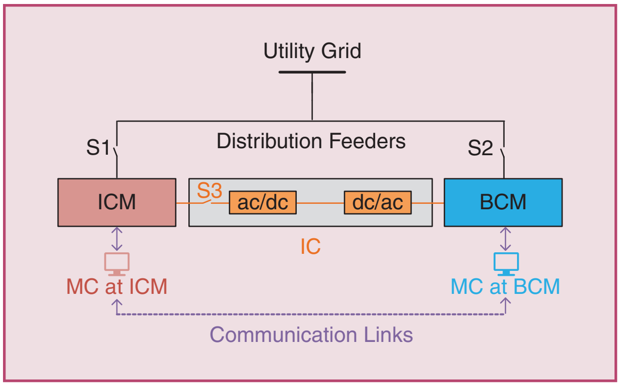

figure 2. A conceptual integration of the IIT-Bronzeville networked microgrids.

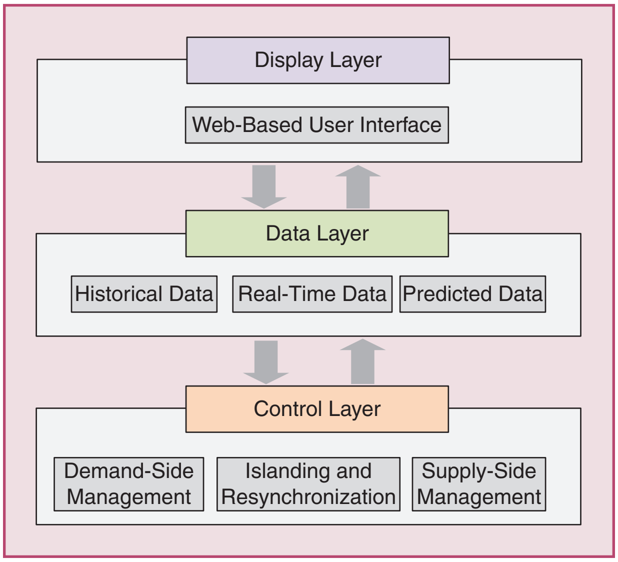

figure 3. The implementation of a microgrid master controller.

layers: data, control, and display. The data layer collects and archives measured field device data and predicts the microgrid operating state. The control layer continuously receives data from the data layer and issues supervisory control signals to dispersed field devices. The display layer, implemented in a web-based application, visualizes the pertinent data required by human operators.

Operational Characteristics of Networked Microgrids

The operation of networked microgrids is more complicated than that of a single microgrid as the microgrids cooperate based on specifically proposed configurations. Accordingly, the energy management system of the networked microgrids coordinates individual microgrid operations to achieve operational efficiency and security for the entire cluster of microgrids.

Operating Modes of the IIT-Bronzeville Networked Microgrids

Networked microgrids can be operated in either an islanded or a grid-connected mode. In a grid-connected mode, they are normally connected to the utility grid in a radial or loop topology configuration. When the utility grid fails to function properly, networked microgrids will be reconfigured to be islanded from the utility grid upon the detection of any frequency or voltage excursion at the PCCs. In Figure 2, if the IC switch S3 is open, there will not be any exchanges between the ICM and BCM, and the operation of the two microgrids will be decoupled and controlled independently. Otherwise, the operation of the two microgrids will be tightly controlled via the IC, which enhances the operational efficiency and security of the individual microgrids.

Table 1 lists the possible operating modes of the networked microgrids depicted in Figure 2. The two microgrids are operated independently in modes 1–4 (whether or not they are connected to the utility grid), whereas the operation of the two microgrids is coordinated in modes 5–8. Generally, the operation of the networked microgrids can be switched seamlessly between any two modes listed in Table 1. In each mode, the networked microgrids satisfy operational requirements posed by customers and contractual obligations with the utility grid (if any).

Figure 4 shows four possible types of networked microgrid configurations listed in Table 1, when the two microgrids are interconnected and their operation is coordinated for demonstrating the potential benefits.

Two-Layer Energy Management Mechanism for Networked Microgrids

The operation of the networked microgrids in Figure 2 is managed in a leader–follower mode, in which the BCM acts as the leader (i.e., the BCM determines power exchanges of the networked microgrids with the utility grid and between the two microgrids) and the ICM cooperates with

table 1. Operating modes of individual microgrids in the networked microgrids.

Mode	S1	S2	S3	ICM	BCM	Configuration of Networked Microgrids	Operation of Networked Microgrids
1	Open	Open	Open	Islanded	Islanded	Islanded	Independent
2	Closed	Open	Open	Grid connected	Islanded	Islanded	Independent
3	Open	Closed	Open	Islanded	Grid connected	Islanded	Independent
4	Closed	Closed	Open	Grid connected	Grid connected	Grid connected	Independent
5	Open	Open	Closed	Islanded	Islanded	Islanded	Coordinated
6	Open	Closed	Closed	Islanded	Grid connected	Grid connected	Coordinated
7	Closed	Open	Closed	Grid connected	Islanded	Grid connected	Coordinated
8	Closed	Closed	Closed	Grid connected	Grid connected	Grid connected	Coordinated

the BCM by following certain supervisory control commands. When the operation of the two microgrids is coupled, the optimal energy management of the networked microgrids cannot be simply obtained by adding the optimal energy management of the two individual microgrids. In particular, power exchanges via the IC will be strategically determined for coordinating the operation of the two microgrids.

Figure 5 shows the composition of the proposed coordinated control mechanism, which is divided into two coordinated layers for facilitating the operation of the networked microgrids. In the upper layer, the MC in the BCM determines the optimal exchange of power with the utility grid and between the two microgrids. The BCM MC interacts continuously with the utility control center for acquiring real-time information while monitoring the operating states in both microgrids. In the lower layer, the MC in each microgrid manages operation independently for satisfying the designated power exchanges. Each MC will communicate with its local controllers (LCs) in response to any changes in real-time operating conditions to regulate microgrid frequency and voltages. The DER functions in the two microgrids include grid-forming and grid-following controls, which are configured by individual LCs. The grid-following control is applied to nondispatchable DERs (e.g., photovoltaics and wind turbines), which will not provide voltage and frequency regulation; such DERs are treated as negative loads. The grid-forming control applies to dispatchable DERs (e.g., combined heat and power units, diesel generators, BESSs) for controlling voltages and the frequency.

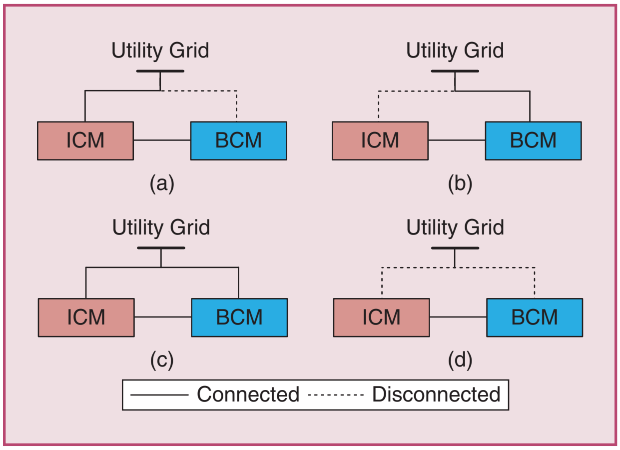

figure 4. Possible configurations for networking the two microgrids.

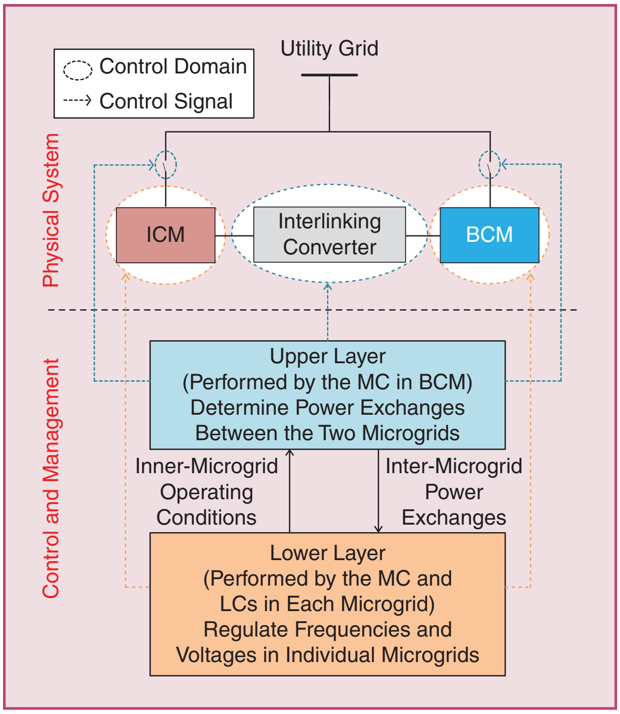

figure 5. Two-layer energy management for networked microgrids.

Hierarchical Control of Islanded Networked Microgrids

Among possible configurations for operating networked microgrids, the islanded operation is the most challenging option. When the IIT-Bronzeville networked microgrids are islanded, the two microgrids cooperate to regulate their frequency and voltages using a two-layer control framework.

Lower-Layer Control: Regulating Frequencies and Voltages in Individual Microgrids

When the networked microgrids are islanded, the individual microgrid frequency and voltages are regulated by grid-forming DERs governed by their respective droop characteristics. Given that the output impedance of the associated power-electronics-based converter is inductive (after introducing virtual inductive impedance), linear droop characteristics are utilized in each grid-forming DER for governing the output of real and reactive power. According to the droop characteristics, an increase in real power output of DERs corresponds with a lower microgrid frequency; likewise, an increase in the DER reactive power output corresponds with a lower terminal voltage.

The following hierarchical control strategy is utilized to facilitate the frequency regulation in a microgrid:

- ✔ Primary control utilizes the frequency-real power droop characteristic to control grid-forming DERs for a fast sharing of real power demand in the microgrid.
- ✔ Secondary control performs corrective actions at the DER level to eliminate any frequency deviations from the respective set points.
- ✔ Tertiary control optimizes energy management at the MC level for assigning proper set points to grid-forming DERs for frequency regulation.

The same hierarchical control principles, based on droop characteristics for voltage regulation, will relate terminal voltages to the reactive power generation of grid-forming DERs, as summarized in Table 2.

table 2. Droop control for regulating voltages and frequency.			
Control Level	**Timescale**	**Function**	**Implementation Level**
Primary	Milliseconds	Realize proportional sharing of real and reactive power demand	LC
Secondary	Seconds	Restore frequency and voltages to set points	LC
Tertiary	Minutes or event driven	Optimize set points for frequency and voltages	MC

Figure 6 illustrates the hierarchical control strategy applied to a grid-forming DER for regulating microgrid frequency. In this case, the DER is initially operated at point a, representing its initial set point. Once the microgrid suffers a real power shortage (e.g., switched to the islanded mode), the real power output of DER will be adjusted for primary control to supply the power deficit according to the droop characteristic. Subsequently, the operating point will be shifted to point b, representing an increase in the DER power output at a reduced frequency. The secondary control will then take place for mitigating the regulation error introduced by the primary control. The secondary control restores the DER operating frequency at its set point by maintaining the adjusted real power output at point c. The tertiary control identifies point d as the optimal DER power output without readjusting the microgrid frequency. The secondary and tertiary controls shift the droop characteristics up or down by applying proportional, integral, and derivative controllers for error compensations.

Upper-Layer Control: Regulating Power Exchanges Between Networked Microgrids

When the IIT-Bronzeville networked microgrids are islanded from the utility grid, the operation of the two microgrids is coordinated by enabling power exchanges via the IC. The MC in the BCM is responsible for issuing supervisory commands that regulate power exchanges between the two microgrids. When one microgrid encounters a power imbalance, the other microgrid will provide support by exercising the power exchange determined by the MC in the BCM. Without the loss of generality, we assume an adequate level of reactive power is already supplied at each microgrid level; therefore, the IC will only consider real power transfer for adjusting operating frequencies of both microgrids.

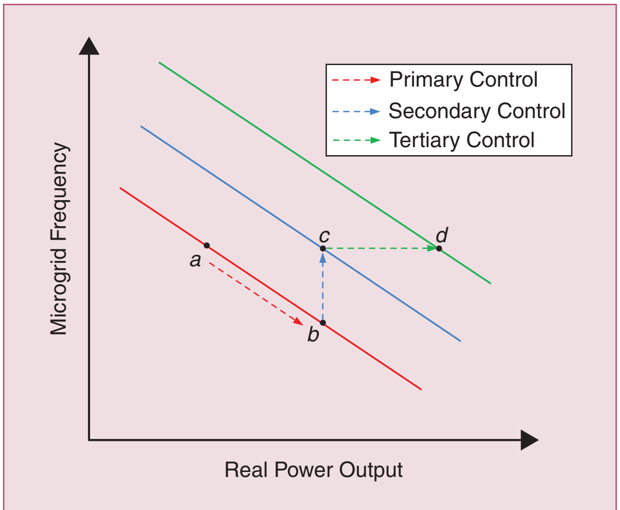

figure 6. Hierarchical control for microgrid frequency regulation.

The coordination of the two microgrids is based on the comparison of their steady-state frequencies. In principle, the two microgrids can be operated at different frequency set points, and thus the normalized values of frequencies should be compared in those cases. The difference between the corresponding normalized values represents the coordination error for the two microgrids. The two microgrids are normally operated at the same frequency, 60 Hz, and thus the coordination error, which represents the deviation of the ICM frequency from that of the BCM, ideally reaches a zero value at steady state. The two microgrids are then coordinated as follows. When the ICM frequency is higher than that of the BCM (i.e., the coordination error is positive), real power is transferred from the ICM to the BCM; when the BCM frequency is higher (i.e., the coordination error is negative), real power flows from the BCM to the ICM.

The MC in the BCM determines the power exchange between the two microgrids based on the coordination error, which is shown in Figure 7 using the coordination droop characteristic. Note that the proposed coordination droop curve includes a vertical deadband where the power exchange has a fixed value. Accordingly, minute coordination errors do not constitute any power exchanges for technical or economic considerations.

A hierarchical control mechanism is developed for regulating power exchanges between networked microgrids. The primary control applies a quick response to steady-state frequency variations in any of the networked microgrids. For the primary control of coordinating the operation of the two microgrids, the MC in the BCM determines the direction and flow of real power transfer for mitigating any coordination errors. Here we present an example to illustrate the role of the primary control in the networked microgrids, where the frequency regulation curve of each microgrid is obtained by aggregating frequency-real power droop characteristics of on-site grid-forming DERs, as illustrated in Figure 8. Initially, there is no power exchange assumed between the two networked microgrids. Consider the case shown in Figure 8(a), in which the power shortage in the ICM drives its steady-state operating point from a to b, while the BCM retains its operating point d. The coordination error for the ICM frequency deviation corresponds to point A (within the deadband) with no real power transfer between the two microgrids. However, when the ICM suffers a more severe power shortage, as shown in Figure 8(b), its operating point will be shifted from a to b, which triggers a power transfer from the BCM to the ICM, represented by point A in Figure 8(b). To supply the designated power export, the BCM increases its real power generation, which shifts its operating point from d to e. Accordingly, the ICM frequency increases as its operating point is shifted from b to c. The power exchange will reduce the difference in the steady-state frequencies of the two microgrids.

Once both microgrids have restored their rated frequencies, the secondary control in the BCM (leader) will adjust the coordination droop characteristic to reflect the new operating condition of the networked microgrids while retaining the amount and the direction of real power transfer resulting from the primary control. Accordingly, the secondary control will shift the set point of real power transfer from A to B by shifting the coordination droop, as shown in Figure 9. However, if the primary control does not detect any power exchanges, the secondary control will not result in any shifts in the coordination droop curve.

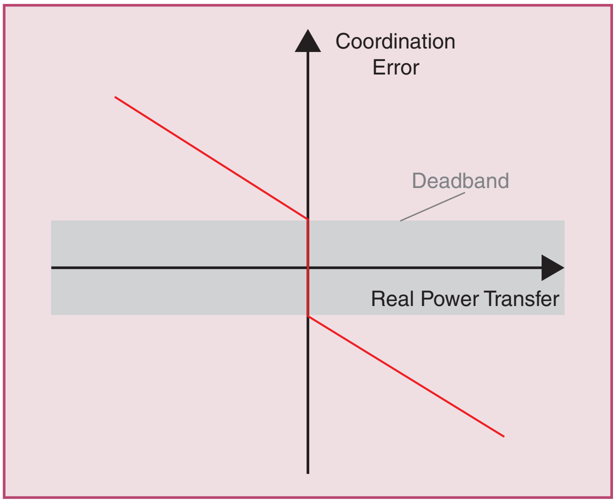

figure 7. The coordination droop curve in networked microgrids.

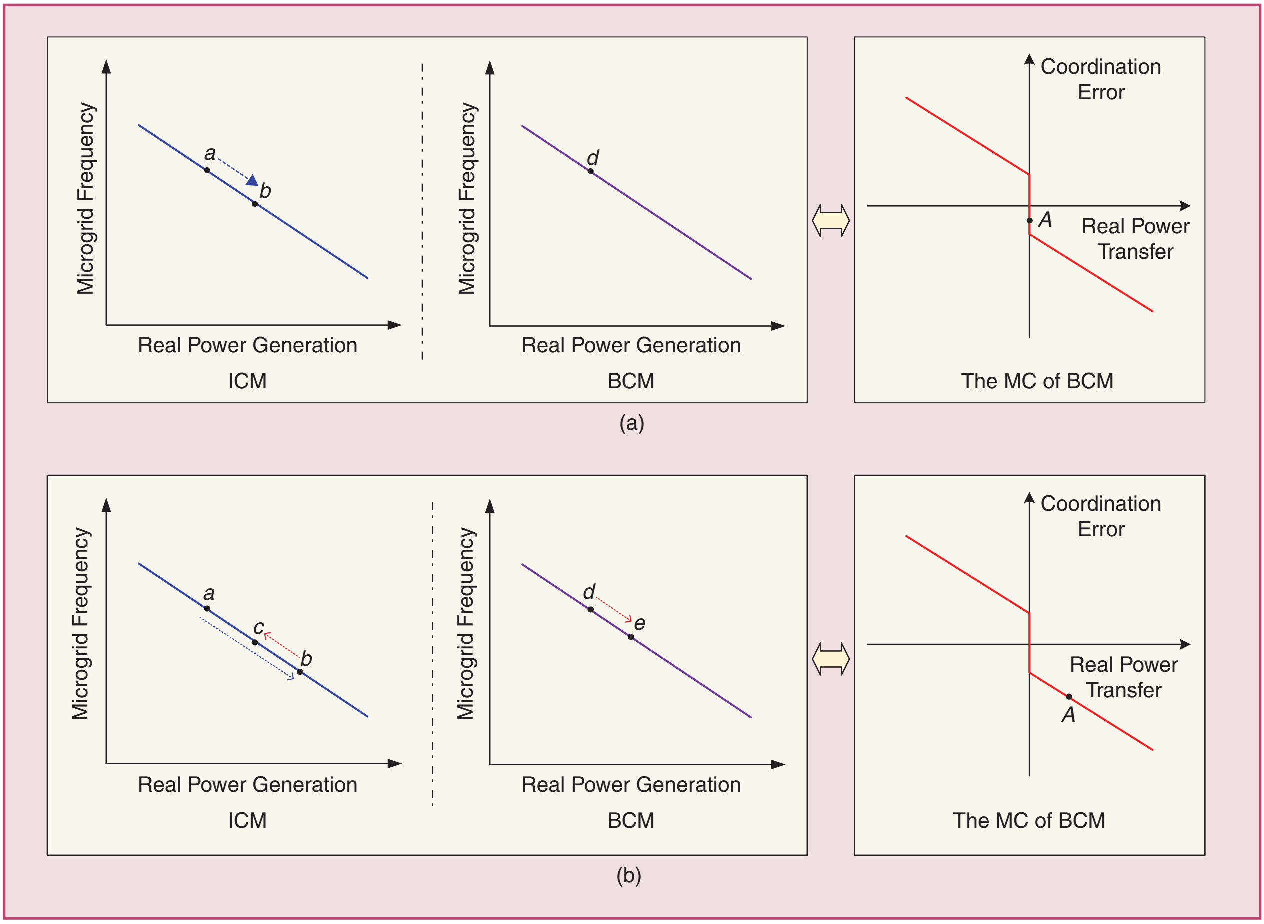

figure 8. Primary control for coordinating the operation of networked microgrids: (a) when the power exchange does not occur and (b) when the power exchange occurs.

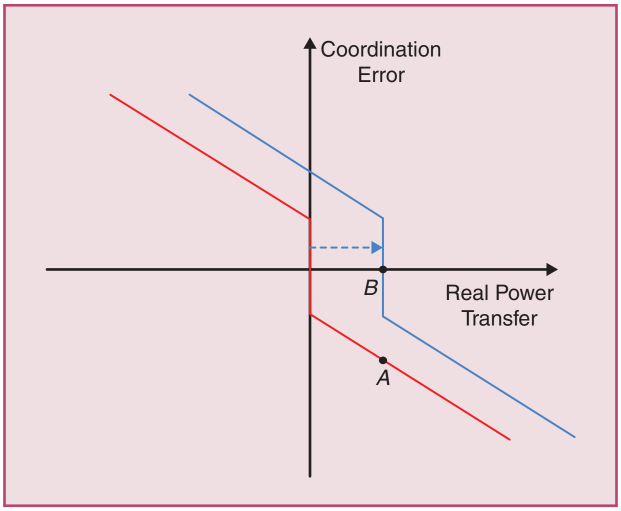

figure 9. Secondary control for coordinating the operation of networked microgrids.

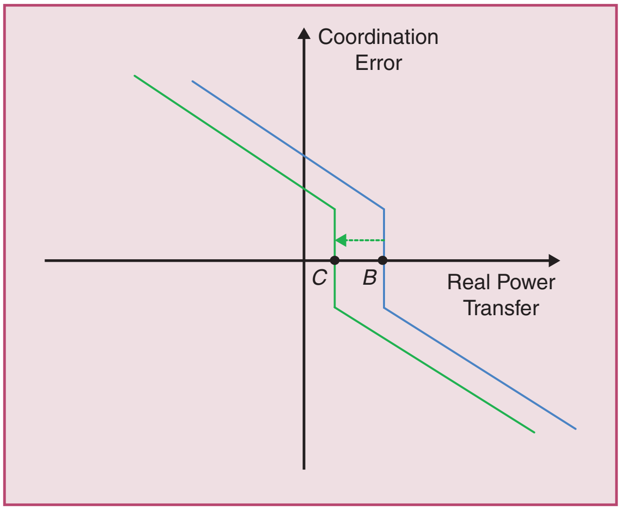

figure 10. Tertiary control for coordinating the operation of networked microgrids.

The tertiary control will optimize the power exchange once each microgrid is settled at its rated frequency. It is represented by shifting the coordination droop curve in Figure 10, where the set point of real power transfer is shifted from B to C. In principle, the tertiary control can also adjust the width of the deadband and the slope of the coordination droop curve by considering technical capabilities and cost characteristics of the networked microgrids.

Hierarchical Control Strategies for Multiple Networked Microgrids

The proposed two-layer control framework can be extended to a multitude of networked microgrids comprising heterogeneous microgrids (i.e., ac, dc, or hybrid ac/dc microgrids). In Figure 11, a leader–follower mode of operation is considered for coordination in which the upper layer is represented by one of the participating microgrids, designated as the leader for managing the

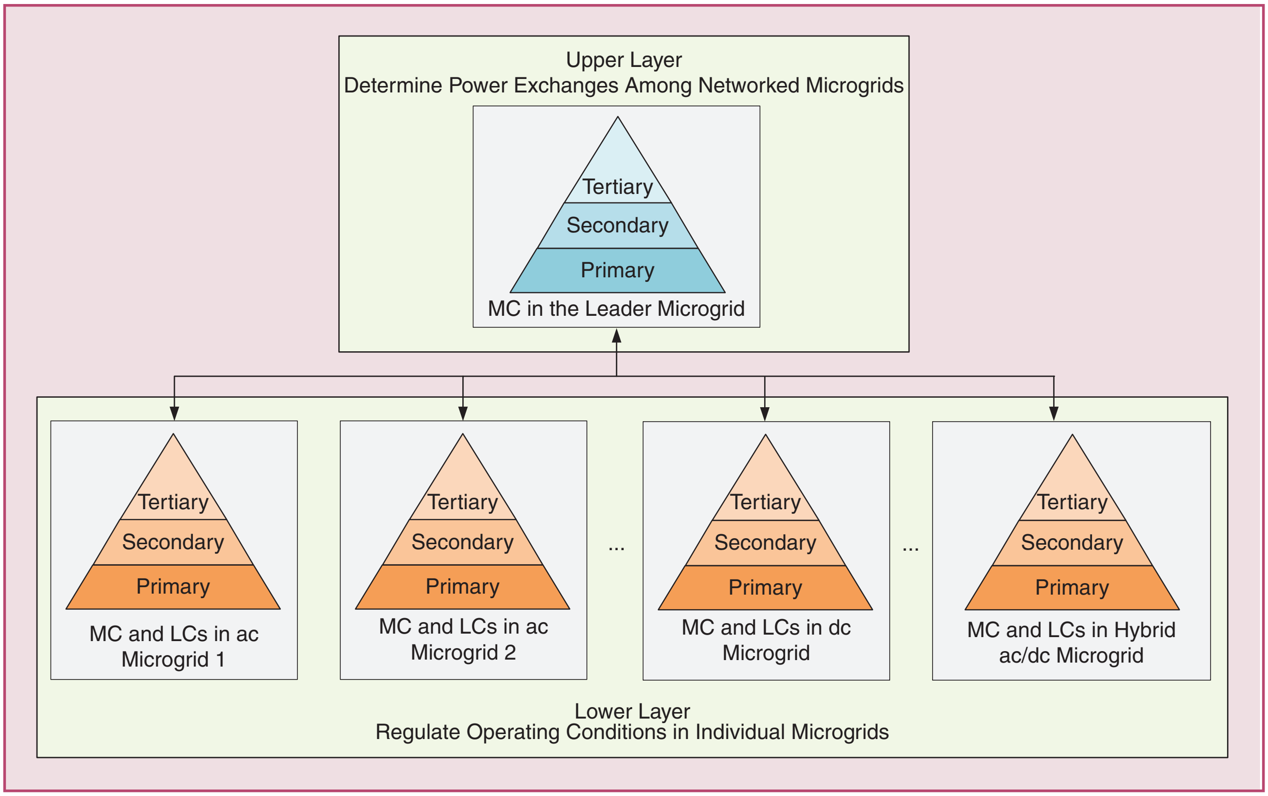

figure 11. A hierarchy of control strategies in networked microgrids.

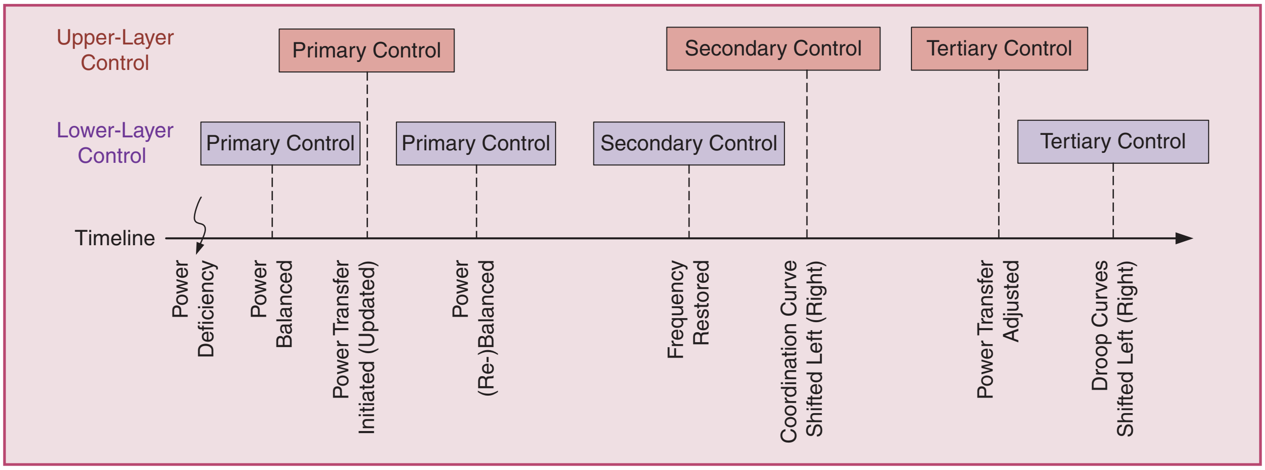

figure 12. The time line for hierarchical control strategies applied in networked microgrids.

exchanges among networked microgrids. At the lower layer, the hierarchical control within individual microgrids will implement the exchange flows designated at the upper layer.

Figure 12 illustrates the coordination principles for interactions between upper- and lower-layer control strategies. Once the lower-layer primary control results in lower microgrid frequency, the upper-layer primary control is employed to support microgrid frequency by updating the power transfer among microgrids. Subsequently, microgrids reapply the lower-layer primary control using the power exchanges designated at the upper level. Next, the lower-layer secondary control in Figure 12 is considered for all microgrids to restore the respective frequencies and voltages to their initial set points. At this time, the initial power transfers resulting from the primary control are considered to be fixed. The upper-layer secondary control will subsequently take action for updating the coordination droop characteristic without modifying the frequency adjustments in individual microgrids at the lower layer. Next, to optimize energy management in the networked microgrids, the upper-layer tertiary control will determine the optimal power exchange among microgrids, followed by the lower-layer tertiary control for the optimal energy management in individual microgrids.

Conclusions

Driven by descending costs of DERs, microgrids are becoming more appealing for managing the variability of renewable energy. This article has explored the possibility of clustering adjacent microgrids to form regionally networked microgrids. Networked microgrids are operated in close coordination so that they can improve the operational performance of individual microgrids. In case the operation of the utility grid is affected by any disruptive events, networked microgrids utilize their inherent capability for self-organizing and self-healing of resources, which can protect local power services. In practice, networked microgrid operations will benefit both the utility grid and electricity customers as microgrids enhance power system reliability, resilience, economics, security, and sustainability. The networking of microgrids is potentially advantageous to strengthening the role of distributed systems in smart grid implementation.

For Further Reading

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