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Controller Hardware-in-the-Loop (CHIL) Testing and Verification of Networked Microgrids

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SUMMARY

Microgrids facilitate higher penetration of renewable-based energy resources and enhancement of resilience of the power grid. In grid-connected mode, a microgrid can provide ancillary services to the grid such as peak shaving, load shifting, renewable firming, frequency regulation, and reactive power support for voltage regulation. When the main grid is not available, microgrid can isolate and continue supplying power to its load utilizing local Distributed Energy Resources (DERs). In modern power distribution systems, the number of microgrids are expected to rise significantly to enable clean, green, and resilient power systems. As more microgrids come online, microgrids that are geographically closer can interconnect to form a network/cluster of microgrids, which enables higher resilience and flexibility. Chicago-based Commonwealth Edison (ComEd), which serves more than 4 million customers across northern Illinois, or 70 percent of the state's population, is installing a community microgrid in the South Side neighborhood of Bronzeville. The Bronzeville community microgrid (BCM) will be able to island and continue supplying power to the customers in Bronzeville independent of the main grid. It will also be able to cluster with the neighboring Illinois Institute of Technology (IIT) campus microgrid (ICM). ComEd has designed and developed a microgrid master controller (MMC) for BCM that enables clustering and de-clustering of the BCM with ICM. A control hardware-in-the-loop (CHIL) test setup had been developed in the lab that utilizes digital twin models of the two microgrids in a real-time digital simulator (RTDS). The RTDS is interfaced with selected distribution automation (DA) devices and DER controllers. This paper shares the design, testing results and learnings from comprehensive testing of clustering of BCM and ICM.

KEYWORDS

Microgrid Master Controller (MMC), Microgrid Clustering, Microgrid De-clustering, Networked Microgrids, Control Hardware-in-the-loop (CHIL), Distributed Energy Resources (DERs).

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INTRODUCTION

The integration of large number of renewable-based DERs without degrading the reliability and power quality is a key challenge in planning and operation of modern power distribution systems. Additionally, the threat of power grid outages due to the extreme weather events such as storms, hurricane, wildfire, heat waves, and cold waves is increasing. These outages not only cause huge economic losses but also elevate the public safety risks. Ensuring the power grid remains resilient to these high-impact events is another challenge for power grid operators. Microgrids have evolved as a technology solution to enhance grid resilience and support higher integration of renewable energy resources. A microgrid is a group of interconnected loads and generators that can operate both in grid-connected mode and islanded mode [1]. In grid-connected mode, microgrids provide grid-support functions. During the grid outage, it can isolate from the main grid and operate independently where it continues to supply available power to the customers in its footprint. Microgrids can be the building block in modern active distribution systems. The control, coordination, and protection are addressed locally at a microgrid level while the higher-level supervisory controllers provide set points to ensure that the entire power system operates in a desired way [2].

Guided by the policies and goals towards clean, green, sustainable, and resilient power supply, utilities along with research institutes, technology partners, government institutes, and communities are actively working towards higher integration of renewable-based energy resources and installation of microgrids. As more microgrids are installed, the microgrids located geographically closer can be interconnected to form a network/cluster of microgrids. Chicago-based Commonwealth Edison (ComEd), which serves more than 4 million customers across northern Illinois, or 70 percent of the state's population, is installing a community microgrid in the South Side neighborhood of Bronzeville. The Bronzeville Community Microgrid (BCM) is planned to cluster with the neighboring Illinois Institute of Technology (IIT) campus microgrid (ICM) [3-4]. A clustered microgrid enables resource sharing among the participating microgrids. If the local resources of a microgrid are exhausted and there is likelihood of shortage of power, it can cluster with the neighboring microgrids and import power to meet the load. Clustering helps in achieving optimal resource scheduling among the microgrids and enables higher flexibility and efficiency of the entire system. Overall, networked microgrids enable higher stability margin and better grid reconnection support when required. In other words, a microgrid cluster adds another layer of resilience in the operation of electric power systems, allows better utilization of the DERs, reduces overall cost, and provides ancillary services [5-7].

The concept of interconnecting microgrids to form networked microgrids can be found widely in literature [3-8]. However, most of these studies are limited to theoretical concepts. This paper presents the design of clustering a utility microgrid and a campus microgrid that has been implemented in a commercial microgrid master controller (MMC) for BCM and tested using a comprehensive control hardware-in-the-loop (CHIL) test setup. The paper discusses the clustering/de-clustering process, results, experiences, challenges, and learnings from testing of microgrid clustering and de-clustering.

BCM, ICM, AND MICROGRID MASTER CONTROLLERS

This section briefly introduces the two microgrids—BCM and ICM—that are considered in this study. The concept of MMC that manages and controls the operation of the microgrid is also discussed.

Bronzeville Community Microgrid (BCM)

Figure 1 shows the one-line diagram of the BCM. It consists of two feeders connected to the main grid via two point of interconnection (POI) switches, POI-1 and POI-2. It is powered by a mix of DERs—a 4.8 MW gas generator, 750 kW PV system, and 500 kW/2000 kWh battery energy storage system (BESS). The two feeders can be interconnected to transfer load from one feeder to the other, thanks to the availability of three tie-switches (T1, T2 and T3). BCM will provide resilient power to the customers in Bronzeville, and it will also be able to cluster with the neighboring microgrid, the ICM.

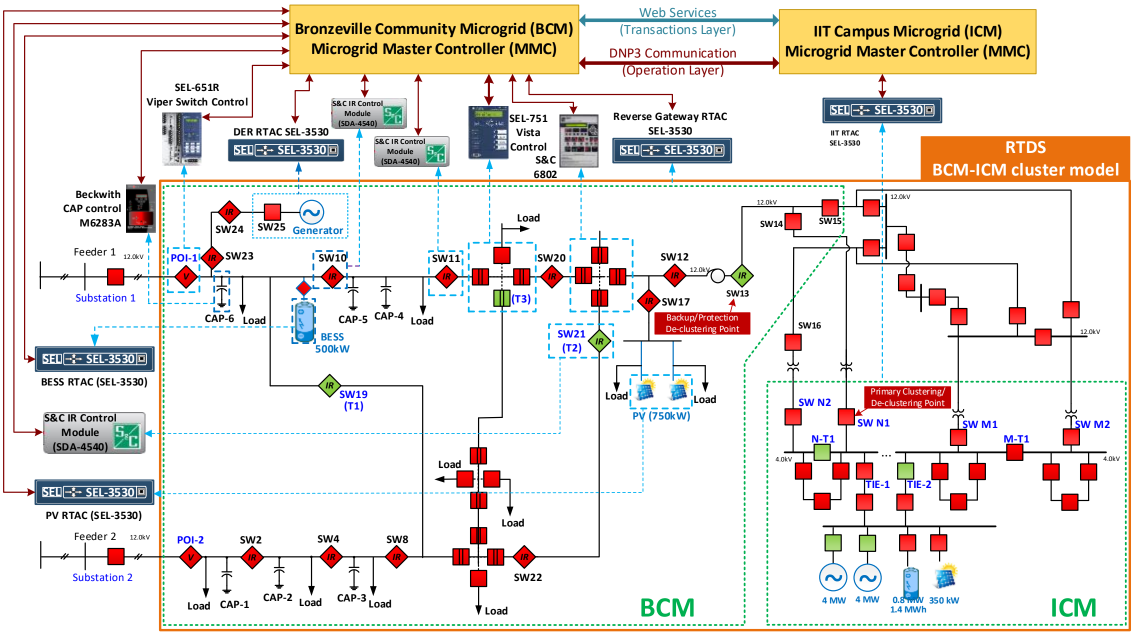

Figure 1 One line diagram of BCM and ICM with MMC and RTDS-CHIL test setup

In grid-connected mode, the BCM provides grid support functionalities such as peak shaving and solar photovoltaic (PV) and battery coordination (SBC). During peak shaving, the microgrid utilizes the local DERs especially the BESS to supply power to the load, hence reduce the power import from the main grid. This way the main grid does not see an increase in the load beyond a defined limit even if the load in the microgrid is above the limit. The SBC functionality utilizes the BESS to compensate the stochastic nature of the PV such that the PV and BESS together act as a dispatchable unit. All DERs in the BCM footprint operate in grid-following mode when the microgrid is operating in grid-connected mode.

In absence of the main grid, BCM can disconnect from the main grid by opening the POI-switch(es) and continue to supply power to the customers. In islanded mode, the gas generator acts as a grid-former while the PV and BESS continue to operate in grid-following mode. Since all DERs in BCM are in the top feeder (Figure 1), top feeder can island from rest of the system by opening POI-1 and tie switches to form partial islanding. In full islanding, two feeders are interconnected via one of the tie switches and both POI switches open to island entire BCM from the main grid. After a system blackout, the BCM can also black-start and restore the microgrid, thanks to the availability of controllable gas generator.

IIT Campus Microgrid (ICM)

The one-line diagram of ICM is also shown in the right side of Figure 1. The ICM has 4 POI switches—SW-M1, SW-M2, SW-N1 and SW-N2—to connect to the main grid. ICM is also fed by the mixture of several DERs—8 MW gas generators, 800 kW/1400 kWh BESS, and 350 kW PV system. Similar to BCM, the ICM can operate in grid-connected mode as well as islanded mode. In grid-connected mode, ICM participates in frequency regulation with Pennsylvania-New Jersey-Maryland (PJM)

Table 1 Statuses of major switched of BCM and ICM at different operating modes

Operating modes	BCM Switches						ICM Switches							
	POI-1	POI-2	T1/T2/T3	SW-13	SW-14	SW-15	SW-M1	SW-M2	M-T1	SW-N1	SW-N2	N-T1	Tie-1	Tie-2
Normal Operation	C	C	O	O	C	C	C	C	C	C	C	O	C	O
Load Transfer1	O	C	C	O	N/A	N/A	C	C	C	O	O	C	C	C
Load Transfer2	C	O	C	O	C	C	O	O	C	C	C	O	C	C
Partial Island	O	C	O	O	C	C	O	O	C	C	C	O	O	C
Full Island	O	O	C	O	N/A	N/A	O	O	C	O	O	C	C	C
Partial Cluster	O	C	O	C	C	O	O	O	C	C	O	C	C	C
Full Cluster	O	O	C	C	C	O	O	O	C	C	O	C	C	C

*C: Closed, O: Open, N/A: Not Applicable interconnection. In absence of the main grid, the POI switches are opened and the ICM utilizes the local DERs to continue supplying power to the microgrid load. In grid-connected mode, all DERs operate in grid-following mode. In islanded mode of operation of the microgrid, the gas generator acts as a grid-forming source while other DERs remain in grid-following mode. Table 1 shows the status of the major switches in BCM and ICM during different mode of operations of the microgrid.

Microgrid Master Controller (MMC)

The operation of microgrids imposes several challenges:

1) Microgrid should be able to operate in various modes, at least in grid-connected and islanded modes, and transit from one mode to another seamlessly.
2) Depending on mode of operation, availability of DERs, and loading condition, the power flow in a microgrid keeps changing in different sections. This imposes challenges in protection coordination and should be recalibrated automatically if network changes [9-10].
3) Uncertainty in power generation from renewable-based DERs such solar PV imposes challenges in optimal scheduling of resources. Moreover, the intermittent nature of these resources introduces power disturbances to the microgrid that are significant in an islanded microgrid with high penetration of such resources [11-12].
4) Challenges in black-start and restoration of the microgrid after a system outage.

The existing legacy distribution supervisory control and data acquisition (SCADA) system has limited visibility over the assets at the microgrid level and cannot operate the microgrid with the required level of granularity. Therefore, MMCs are required for management, control, coordination, and operation of microgrid assets [13]. They can also interface with utility's SCADA system to ensure coordination with utility grid operation. The BCM and ICM are controlled and managed by their respective MMCs.

ComEd partnered with Siemens to develop a commercial MMC using SIEMENS microgrid management system (MGMS) platform. The BCM MMC will be deployed to manage the microgrid assets. It performs several functionalities. It has a microgrid optimization module (MOM) that generates optimal schedules of the resources in a microgrid. It also dispatches the energy storage for peak shaving and smoothing the intermittent power from renewable DERs. Moreover, sequence of operation (SOO) is defined and implemented in MMC. An SOO is a set of predefined steps that control the distribution automation (DA) devices, DERs, and other equipment during the transition of microgrid from one mode to another. The SOO allows automatic and seamless transition of microgrid to various modes with minimal operator's intervention. SOO includes several processes such as load transfer, planned islanding, grid reconnection, black-start and load restoration, and restoration of healthy sections of the microgrid after a permanent fault. SOO for clustering/de-clustering with neighboring microgrid(s) has also been developed and implemented in the MMC. The MMCs that manage different microgrids can communicate with each other to request and perform clustering when feasible.

BCM-ICM MICROGRID CLUSTER

Both the BCM and ICM MMCs solve optimization problem to determine the optimal scheduling of the DERs depending on mode of operation of microgrid, PV forecast, load forecast, and state of charge of storage system. During system outages, both microgrids are expected to isolate from the grid and operate in islanded mode. When both microgrids are in islanded mode and any of the MMCs foresee the shortage of power in near future, it can request the other MMC to provide power support via clustering. In current design, the power is only expected to flow from ICM to BCM in clustered mode. Therefore, only BCM can request for support to ICM whenever the BCM MMC foresees the power shortage and the ICM provides agreed power. In Figure 1, the primary point of clustering (POC) and de-clustering is SW-N1 which is monitored and controlled by ICM MMC. ICM performs synchronizes and connects to the BCM at SW-N1.

When the two microgrids are islanded and independent, their respective gas generators act as grid-forming source. Once BCM and ICM are connected 'electrically', the BCM generator continues to operate in isochronous mode while the ICM generator switches to grid-following mode. ICM then exports power to BCM based on the agreement in the transaction process. To de-cluster, ICM zeros out power flow at SW N1 and opens the breaker. For BCM MMC, the power flow feedback comes from SW13. However, for financial aspects of the clustering power exchange, the point of measurement (POM) is at SW-N1 on ICM.

SW13 acts as a backup de-clustering point which is directly monitored and controlled by BCM MMC. It is a DA device that trips on typical POI protection settings in both directions. In other words, SW13 trips on faults on either sides (BCM or ICM) and isolates the two microgrids from each other.

There are two layers of communication between the BCM MMC and ICM MMC for clustering/de-clustering processes:

1) Transaction layer: The transaction of bids is performed via web services API (Application Programming interface), and
2) Operation layer: Once the bids are awarded, the two MMCs utilize DNP3 for real-time communication and data exchange i.e., send/receive setpoint commands/status.

Clustering Process Flow

The overall clustering process flow for BCM and ICM is shown in Figure 2. Both microgrids should be in islanded mode prior to clustering. When BCM MMC foresees shortage of power in BCM, it sends an emergency request for additional power to the ICM MMC via web services. The emergency request has attributes such as microgrid name, microgrid ID, request ID, server name, time of request, requested minimum power, requested maximum power, start time, and end time. If the ICM is also in islanded mode, the ICM MMC submits a bid in response to the request. The bid has following attributes—microgrid name, microgrid ID, bid ID, request ID, server name, current time, minimum power for bid, maximum power for bid, price per kWh, start time, and end time. Any unsolicited bids are excluded at this time. Upon receiving the bid, the BCM MMC performs optimization to evaluate the bid and notifies ICM MMC about the bid award details. The award details include microgrid name, microgrid ID, request ID, server name, bid ID, current time, bid acceptance or rejection flag, rejection reason, cleared kW, cleared price, desired power factor, start time, and end time. Once the bid is awarded, BCM MMC notifies the BCM operator that clustering is required for 'electrical' connection of two microgrids. The BCM operator enables the clustering, the BCM MMC and ICM MMC execute the clustering SOO to connect the two microgrids.

The BCM MMC executes following SOO for safe and seamless transition of the microgrids from islanded mode to cluster mode.

1) Open command to SW-15 to avoid connection to grid when the microgrids are clustered.
2) Close command to SW-13.
3) Close command to SW-14, if open.
4) Send 'Initiate clustering' command to ICM MMC.

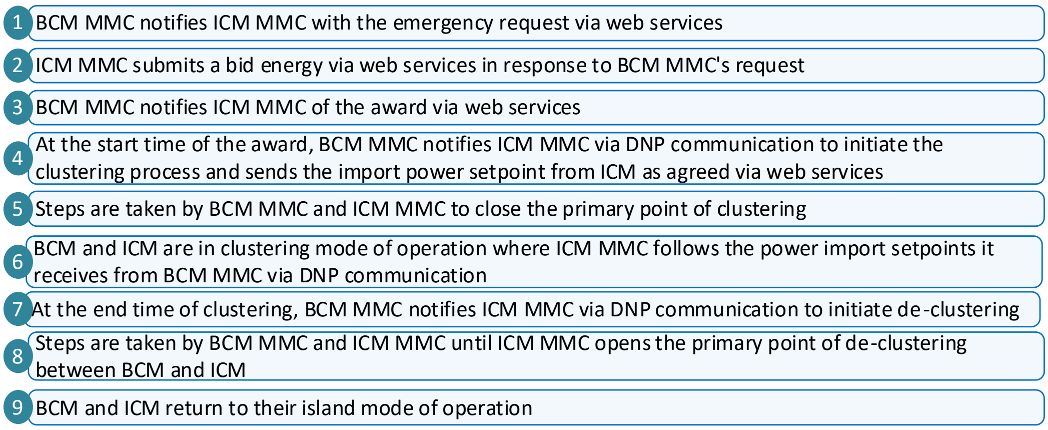

Figure 2 BCM-ICM clustering/de-clustering process flow

On receiving the 'initiate clustering' command from BCM MMC, the ICM MMC synchronizes ICM with BCM and sends close command to SW-N1. SW-N1 closes when the synchronization conditions are met as defined in IEEE Std. 1547 [14]. As soon as SW-N1 closes, the ICM gas generator receives the status of SW-N1 via mirror bit, an IEC 61850 based communication protocol for high-speed data exchange and switches its mode to 'grid-following'. The power transfer occurs only during the award period. Therefore, ICM MMC maintains zero power at POC outside award period. At the start of award-time, the BCM MMC sends agreed power-set point to the ICM MMC, and the ICM MMC controls the DERs to supply this power to BCM.

De-clustering Process Flow

At the end of clustering, BCM MMC sends zero power setpoint to ICM MMC and notifies the operator for de-clustering. Once the de-clustering is enabled, the BCM MMC notifies ICM MMC to initiate de-clustering and MMCs coordinate to complete the de-clustering process as defined in following steps:

1) BCM MMC sends zero power set-point to ICM MMC. ICM MMC adjusts the power of the DERs such that the power flow at SW-N1 is zero (with some threshold).
2) Send 'Initiate de-clustering' command to ICM MMC that opens SW-N1 and disconnect the BCM from ICM. As soon as SW-N1 opens, the ICM gas generator receives the status of SW-N1 via mirror bit and changes its mode of operation to grid forming mode.
3) Open command to SW-13.
4) Close command to SW-15.

At the end of de-clustering process, the two microgrids return to two independent microgrid islands. Note that during clustering, SW-14 is closed by BCM MMC. However, during de-clustering, the BCM MMC does not need to operate on SW-14.

RTDS-HIL TEST SETUP AND TEST RESULTS

Figure 1 shows the schematic of a comprehensive real-time hardware-in-the-loop (RT-HIL) test setup developed at ComEd's Grid Integration & Technology (GrIT) laboratory. The two microgrids are modelled in real-time digital simulator (RTDS). Selected hardware devices are interfaced to form a sophisticated CHIL test setup. The BCM MMC resides in a server in the lab that communicates with individual assets in BCM via a secure DNP3 communication to control and manage them. On ICM side, an SEL-3530 real-time automatic controller (RTAC) is used to mimic the ICM MMC that communicates with the ICM model in RTDS via DNP. In the lab setup, the bidding and financial transactions are done between BCM MMC and a station that hosts the transaction features of the ICM via web services. For operation layer, the BCM MMC communicates with the ICM SEL RTAC via a secure DNP.

For cluster/de-clustering testing, the two microgrids are transferred to full islanding by executing full islanding SOO [13]. Then, the power shortage is created on BCM side by applying limit on gas generator of the BCM. In this study, two test cases are considered. In case I, the maximum power limit is imposed on gas generator at 2500 kW from 12:00 to 14:00 on Day-1. In case II, the power limit on gas generator is 2000 kW from 13:00 to 15:00 on Day-2. Due to this imposed power limit, the BCM MMC foresees the shortage of power in BCM. The emergency notification, bidding request, awarding, and financial

Table 2 Bid award start/end time and cleared kW during the clustering test of BCM and ICM

	Test Case I (Day-1)			*Test Case II (Day-2)*		
SN	**Start time**	**End time**	**Cleared kW**	**Start Time**	**End Time**	**Cleared kW**
1	12:00	12:15	523.16	13:00	13:15	565.08
2	12:15	12:30	506.00	13:15	13:30	550.20
3	12:30	12:45	615.04	13:30	13:45	885.89
4	12:45	13:00	513.59	13:45	14:00	920.15
5	13:00	13:15	503.31	14:00	14:15	1029.90
6	13:15	13:30	520.33	14:15	14:30	1053.02
7	13:30	13:45	884.78	14:30	14:45	1150.88
8	13:45	14:00	920.15	14:45	15:00	1166.43

transaction occur between the MMCs automatically in the lab test setup. The dispatch cycle is of 15 minutes. Therefore, the BCM awards power at 15-minute interval as shown in Table 2. The projection of power shortage may be different from the actual power generation. Therefore, to avoid unnecessary transactions, the BCM MMC is designed to look for power shortage starting within next 2 hours and transactions are done for 2 hours. In other words, if current time is t_{now} and the BCM MMC foresees the shortage of power starting at t_{short}, it sends cluster request to ICM only if $t_{short} \leq t_{now}+2$ hours. During the transaction, the power shortages between t_{short} and ($t_{short}+2$ hours) are considered.

Figure 3(a) shows the voltage, frequency difference, and phase angle difference at the point of synchronization, SW-N1, and the status of the main DA devices during clustering. Initially, both the microgrids are in islanded mode—SW-13 is open, SW-14 is closed, SW-15 is closed, and SW-N1 is open. After the cluster command is issued, the microgrids seamlessly transit to clustered mode from islanded mode. The BCM ICM follows the sequence discussed earlier—a) open SW-15, b) close SW-14, c) close SW-13, and b) send 'initiate clustering' command to ICM MMC. The ICM MMC then sends close command to SW-N1 that checks the synchronization conditions and closes when the conditions are defined. The voltage, frequency, and the phase angle on either side of SW-N1 shown in Figure 3(a) shows the synchronization process. Figure 3(b) shows the de-clustering process. During de-cluster, the power at POC is reduced to zero, then the MMCs follow the sequence—a) open SW-N1, b) open SW-

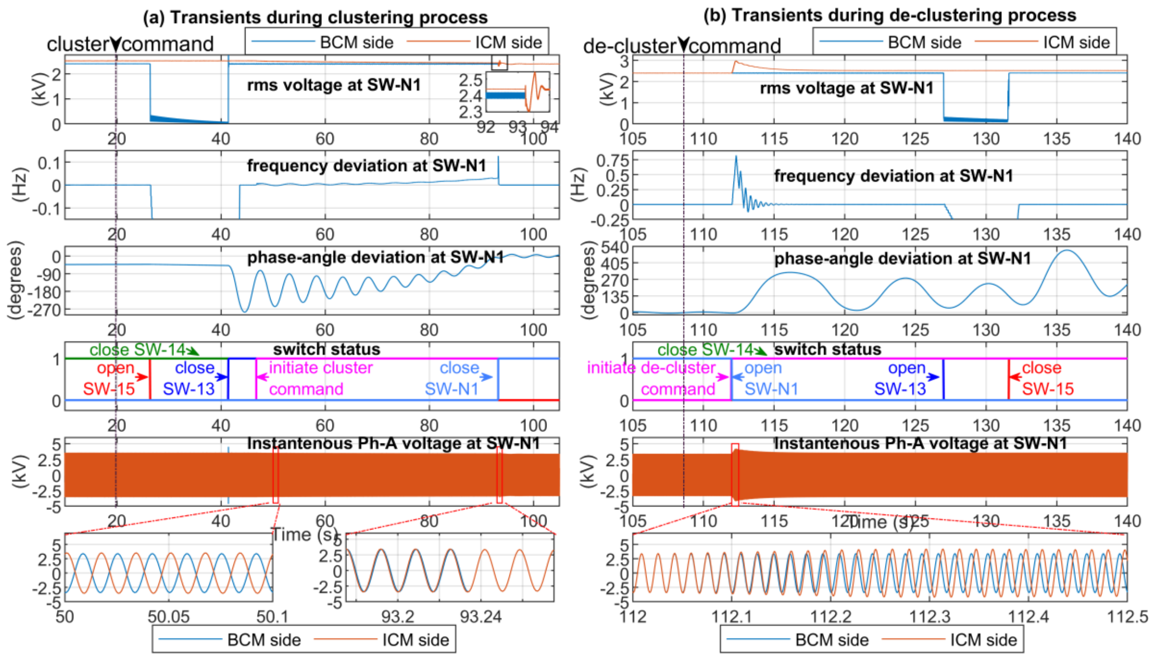

Figure 3 Transient responses during (a) clustering, and (b) de-clustering of BCM with ICM

Figure 4 Power import at POC when BCM and ICM are clustered: (a) Test case I, and (b) Test case II

13, and c) close SW-15—to achieve seamless de-cluster of the two microgrids. The two microgrids return to islanded mode at the end of de-clustering process.

Figure 4 shows the power exchange when the two microgrids are in clustered mode. The power at the SW-N1, the point of clustering, follow the power award shown in Table 2. For smooth power transition, the actual power import starts 2.5 minutes ahead of the award start time and ramps up/down for 5 minutes to reach to the award value. Then the power at SW-N1 remains constant for next 10 minutes before ramping to the next award value. At the end of the award period, the power import is reduced to zero. The operator then starts the de-clustering process.

CHALLENGES IN MICROGRID CLUSTER IMPLEMENTATION AND LESSONS LEARNED

The high penetration of DERs, the fast-evolving grid-forming technologies and widely deployed grid automation devices will support scaled implementation of networked microgrids. The demonstration of BCM-ICM microgrid cluster is the first project in the United States to test the networking of two microgrids on the community level and several challenges have been identified during the implementation:

1) Control coordination between MMCs and DERs: networked microgrids require proper coordination between MMCs and individual DER, especially during clustering/de-clustering procedures that have frequency/voltage synching mandates.
2) Protection challenges: protection schemes of networked microgrids primarily depend on DER type and microgrid operating modes. The upgrade of microgrids with additional DERs shall trigger the revisit of the existing protection schemes and lead to re-design of protection coordination schemes. Adding new microgrids into the cluster will complicate the problem further and ultimately delay the integration process.
3) Cyber-physical security: The cyber-physical security measures need to be carefully re-evaluated when an on-prem MMC interfaces with a cloud-hosted MMC in real-time environment. As the cloud is becoming a mainstream option by vendors, utilities may have to reconsider their architecture on IT and OT to harvest the cloud benefits and maintain the existing security standard.

These challenges require joint effort from electrical engineers, IT specialists and field practitioners and may take months to reach consensus/alignment.

CONCLUSION

As the number of microgrids are increasing in modern power distribution system, the microgrids that are geographically closer can be interconnected and form a microgrid cluster, which enables support among the participating microgrids when in need—this adds another layer of resiliency. ComEd is installing a community microgrid, BCM, that will be able to cluster with a neighboring ICM. This paper presented procedures, results, learnings, and experiences from comprehensive lab testing of clustering of BCM with ICM in a RT-CHIL test setup.

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