A Converter-Based Battery Energy Storage System Emulator for the Controller Testing of a Microgrid with Dynamic Boundaries and Multiple Source Locations

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***Abstract*—Microgrids (MGs) with dynamic boundaries and multiple source locations have been proposed as a future MG concept, which requires sophisticated control and coordination. Testing of MG controllers in a realistic environment becomes essential for the efficient and reliable deployment of such MGs. A converter-based testing platform has been proposed for MG controller evaluation, which requires well-modeled emulators. However, as a core component, existing battery energy storage system (BESS) emulators in the literature cannot meet the testing needs of the MG with dynamic boundaries and multiple source locations. In this paper, a BESS emulator for controller testing of MG with dynamic boundaries and multiple source locations is developed, considering controller functions, different operation modes, and transition coordination. Experimental results are conducted to verify the developed emulator on a converter-based testbed.**

Keywords—Battery energy storage system, converter emulator, microgrid, dynamic boundary, multiple source locations, hardware testbed

I. INTRODUCTION

MG has become a mainstream research topic for distribution-level systems in recent years [1]. Future MGs are trending to be smarter, more capable, and as a result, more complex. One important example is a MG with dynamic boundaries and multiple source locations, which can better utilize the distributed energy resources (DERs) and further enhance resiliency of the grid and its connected loads [2]. Controller implementation is a core part of the MG development. Before field deployment, one essential step of the MG controller implementation is testing [3]. To realize flexible and practical MG controller testing, a converter-based hardware testbed (HTB) has been proposed [4], where power converters serve as emulators to emulate the electrical characteristics of MG components [5]. Realizing suitable emulators will increase the accuracy and practicality of controller testing.

BESS is one of the key components in a MG, which can increase energy usage efficiency and promote MG reliability [6]. BESS can be either applied as the source of an islanded MG independently to support critical loads [7] or complement other sources like wind or solar. In the literature, BESS emulators have been proposed to support testing of a MG with a fixed boundary [8], a MG with dynamic boundaries and one source location [4], and a dc MG [9].

Compared with other MGs, a MG with dynamic boundaries and multiple source locations can change its boundaries with the available DER outputs and form multiple islands, which poses challenges to the MG controller development. First, in the islanded mode, the MG controller needs to coordinate multiple sources to balance the power in real-time between multiple sources and loads as well as regulate the voltage and frequency of the MG. Also, the MG controller is required to determine the boundary of multiple islands simultaneously. Moreover, because of the numerous operation modes and corresponding transitions of this MG, transition coordination also must be accounted for by the MG controller [10]. HTB testing provides a realistic and comprehensive evaluation of the MG controller. To support the HTB testing of this MG, the BESS emulator needs to consider the requirements of different controller functions, multiple operation modes, and more transition coordination, which have not been covered in existing BESS emulators.

Therefore, in this paper, for the HTB testing of the MG controller with dynamic boundary and multiple source locations, control algorithms of the BESS emulator are developed, and the BESS emulator is implemented. The MG controller HTB testing is introduced first. Then, a MG with dynamic boundaries and multiple source locations is discussed. The algorithms required for controller testing are defined, and the BESS emulator is developed. Finally, experimental verifications are provided on a converter-based MG HTB.

The rest of the paper is organized as follows: the MG controller HTB testing is introduced in Section II; Section III covers the concept of MG with dynamic boundary and multiple source locations; the BESS emulator development is illustrated in Section IV; Section V provides the experimental verifications; and the conclusion is drawn in Section VI.

II. MG Controller HTB Testing

A. Testbed Structure

The converter-based MG controller HTB is illustrated in Fig. 1 [4]. Converter emulators are connected through a power circulating structure so that the dc power supply only provides the power losses of the whole testbed. In a converter emulator, a certain MG component model (DER, load, etc.) is integrated to generate the voltage, frequency, and/or current references of the converter. By realizing the generated references through converter voltage/current control, a certain MG component can be emulated. Meanwhile, different MG topologies can be realized by changing the isolation switch and MG topology connections. A MG can be emulated by applying certain converter emulators and corresponding topological connections in the MG HTB. By using the HTB, the MG controller can be tested in a near-grid-like environment with practical factors such as actual power flow, control and communication delays, and measurement noise/error.

B. Control Architecture

The control architecture of MG controller testing is summarized in Fig. 2. The actual MG controller is placed into the emulated MG through communications to realize a

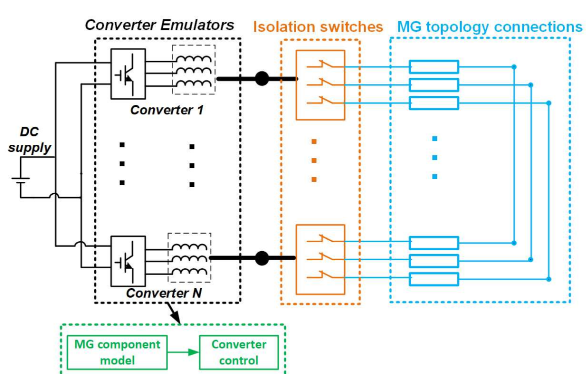


Fig. 1. Converter-based MG controller HTB structure.

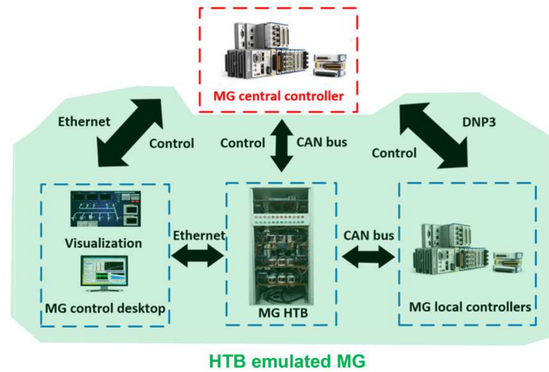


Fig. 2. MG HTB control architecture.

controller in-the-loop testing. From the control perspective, the actual MG controller communicates with the emulated local controller through the DNP3 communication protocol. The local controller controls the MG component emulators. The converter emulators realize the commands issued by the local controller and the real-time measurements are sensed back to controllers for control needs. The visualization interface will also gather the controller commands and emulator feedback to indicate the MG controller status as well as the operation conditions of the emulated MG.

III. MG with Dynamic Boundaries and Multiple Source Locations

A. MG Concept and Operation

An example MG with dynamic boundaries and multiple source locations is shown in Fig. 3, where there are 7 load sections and 4 DERs (2 BESSs, 1 generator, and 1 PV). The four DERs are distributed at two source locations, meaning that two separate islands can be formed in the islanded mode. Island 1 is formed by the BESS1 and island 2 is formed by a backup generator, a PV, and the BESS2. Since island 2 contains PV generation, the boundary of island 2 can potentially be expanded or shrunk based on the available PV power. The two separate islands can merge to be one when PV has sufficient power. The operation modes of this MG include grid-connected mode, islanded mode with one merged island, and islanded mode with two separate islands. Consequently, the various possible transitions of this MG need to be considered.

Transitions include black start, reconnection, and islanding. During the black start transition, two islands need to be enabled to support loads of each island. During the reconnection transition, two separate islands can first merge to be one and then

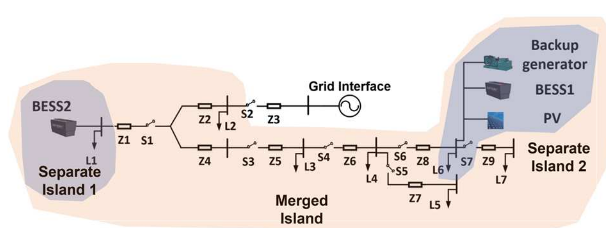


Fig. 3. MG with dynamic boundaries and multiple source locations.

reconnect to the main grid, or two separate islands can reconnect to the main grid independently. During the islanding transition, the MG can also operate as a single merged one or two separate ones based on the PV power. Also, islanding includes planned islanding and unplanned islanding. During planned islanding, the MG controller will regulate the DER powers to realize smooth transients. During unplanned islanding, the MG controller will coordinate with the DERs to detect the islanding condition and reach the islanded operation.

B. Controller Functions

In this MG, the MG controller plays a critical role. The controller functions are summarized in Table I, including the MG information input, recording, long-time functions, and real-time functions [11]. The real-time functions contain steady-state functions and transition functions. The long-time functions focus on MG operation control for a long time period (one day or longer), which contain energy management and forecasting functions. The energy management function is to realize optimal dispatch of switches and sources' power to achieve economic MG operation. The forecasting function is to provide necessary information for energy management. The real-time functions are realized to keep the MG operational. The steady-state functions are designed to achieve real-time power balancing and determine the MG operation status. The transition functions concentrate on the MG mode transitions. The detailed function descriptions can be found in Table I.

TABLE I. MG Controller Functions

Function type	Function block	Descriptions
MG input	Model management	Load system information
	Topology identification	Get the real-time MG topology and smart switch information
	Communication	Link controllers and the MG
	State estimation	Estimate the voltage and angle information of nodes in the MG
Recording	Data logging	Record real-time data
	Event recorder	Record events
Long-time functions	Energy management	Realize optimal dispatch of switches and sources' power to achieve economic operation
	PV/load forecasting	Forecast day-ahead PV/load power for energy management
Steady-state functions	Finite state machine	Determine the operation mode and state of the MG
	PQ balancing	Keep stable voltage and frequency as well as real-time power balancing between loads and sources
Transition functions	Planned islanding control	Switch the MG from grid-connected mode to islanded mode
	Reconnection control	Reconnect the MG to the main grid or merge multiple separate islands to be one
	Black start	Enable the MG from shutdown to the islanded mode
	Protection coordination	Update the smart switch protection curves based on the MG operation mode

IV. BESS Emulator Development

A BESS emulator is developed based on the controller function needs. As summarized in Fig. 4, the required emulator functions include the SOC indication, control in grid-connected mode, control in islanded mode, and transition control.

A. SOC Indication

For the energy management function, the MG controller requires the state-of-charge (SOC) information from the BESS to determine the optimal DER outputs. Therefore, the converter-based BESS emulator also needs to provide the MG controller with SOC information. In an actual BESS, the real-time SOC estimation is complicated, which may require an accurate BESS model or advanced data mining technologies. However, in the MG HTB testing, the purpose is to evaluate the MG controller performance. The BESS emulator only needs to provide the SOC information that can indicate the BESS status.

Therefore, as shown in Fig. 5, in the BESS emulator, assuming the initial condition of the BESS is known, the BESS will update the real-time SOC of the BESS based on the power consumption of BESS. The real-time SOC is calculated as:

$$SOC(t) = SOC(t-1) + P_{ESSS}(t)\Delta t \tag{1}$$

where $P_{BESS}(t)$ is the normalized BESS power at time t. The SOC range is defined as:

$$0 \leq SOC(t) \leq 1 \tag{2}$$

In addition, besides long-time operation functions, the SOC of the BESS will also impact the real-time function testing of the

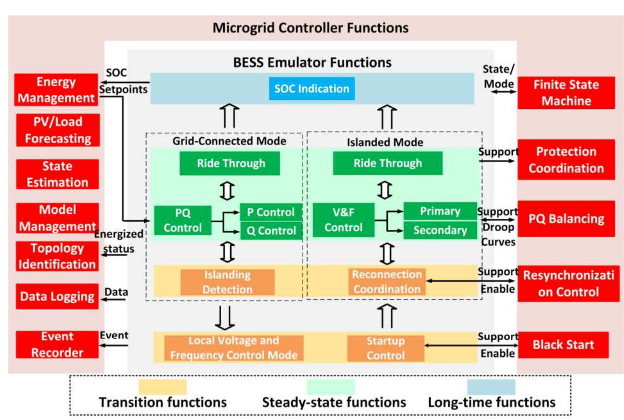


Fig. 4. BESS function requirements from MG controller testing.

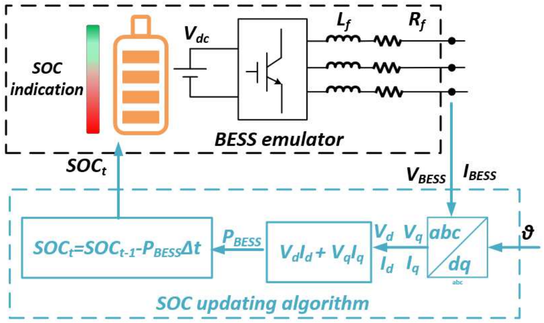


Fig. 5. BESS emulator SOC indication.

BESS. The real-time function also requires the SOC indication to avoid over-charge or over-discharge of the battery.

B. Control Functions in the Grid-Connected Mode

1) Power Control

As shown in Fig. 6, in the grid-connected mode, the MG voltage and frequency are provided by the main grid. The BESS emulator operates in the grid-following (GFL) mode to directly control the output active and reactive power. By realizing this control, the BESS can follow the energy management commands to provide the grid with the required power. The output power is calculated as [12]:

$$\begin{cases} I_d^{ref} = \dfrac{V_q P_{BESS}^{Ref} + V_d Q_{BESS}^{Ref}}{V_d^2 + V_q^2} \\ I_q^{ref} = \dfrac{V_q P_{BESS}^{Ref} - V_d Q_{BESS}^{Ref}}{V_d^2 + V_q^2} \end{cases} \tag{3}$$

where P_{BESS}^{Ref} and Q_{BESS}^{Ref} are the power commands from the MG central controller, respectively. The grid voltage and current information is obtained by the phase lock loop (PLL), which is also shown in Fig. 6.

2) Fault Ride Through

When the grid fault happened, rather than shutting down, the BESS emulator will continue to ride through to support the protection coordination testing of the MG controller. Since the actual BESS inverter usually has a limited over-current capability during fault conditions, the BESS emulator will also limit the maximum output current during the ride through. According to (3), when the grid voltage drops during the fault condition, the current BESS emulator will increase. Once the calculated output current exceeds the limitation, the BESS emulator will reassign the current references of the *dq* axis, which can be described as:

$$\begin{cases} I_{df}^{Ref} = \dfrac{I_{BESS}^{max}}{\sqrt{\left(I_d^{ref}\right)^2 + \left(I_q^{ref}\right)^2}} I_d^{Ref} \\ I_{qf}^{Ref} = \dfrac{I_{BESS}^{max}}{\sqrt{\left(I_d^{ref}\right)^2 + \left(I_q^{ref}\right)^2}} I_q^{Ref} \end{cases} \tag{4}$$

where I_{BESS}^{max} is the BESS current capability; I_{df}^{Ref} and I_{qf}^{Ref} are the output current references during the fault condition; I_d^{Ref} and I_q^{Ref} are the calculated current references from (3). The ride through time follows the IEEE standard 1547-2018 [13].

3) Islanding Detection

Unplanned islanding may be triggered by abnormal conditions like faults. During the unplanned islanding transition, the MG controller has no information about the islanding schedule. Therefore, the MG needs to detect the islanding first and then realize the mode transition. In conventional MGs, the islanding detection strategy can be realized by the MG controller or the DER local controllers [14-16]. However, in the MG with dynamic boundary and multiple source locations, the point of the coupling of the MG is not fixed, meaning that the central controller-based islanding detection strategies may require specific control for all the potential MG boundaries to increase the control complexity and cost. Therefore, realizing the islanding detection with the DERs can be an economic and simple solution.

Since the BESS emulator is regulates the voltage and frequency of the MG in the islanded mode, the islanding

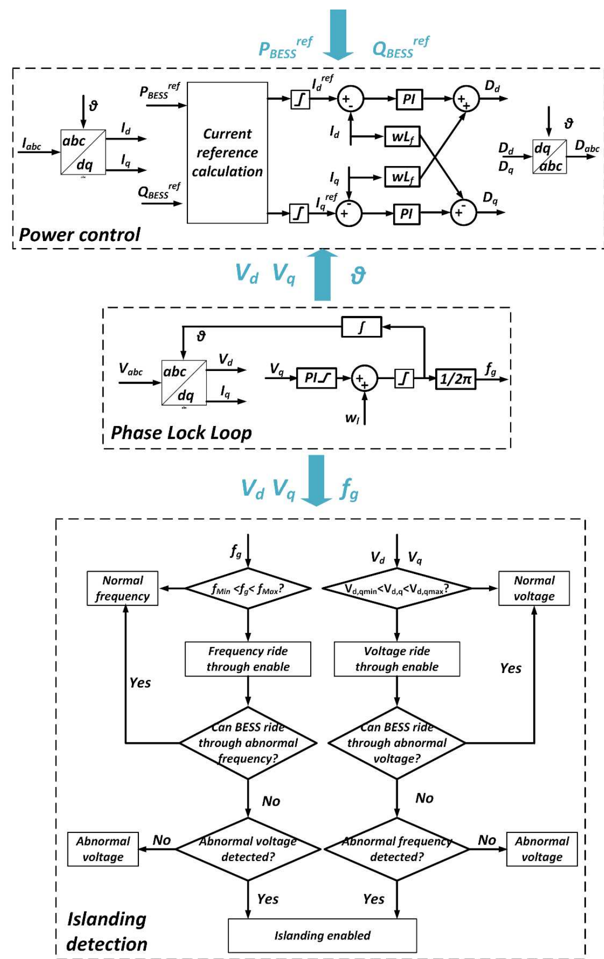


Fig. 6. Control functions in the grid-connected mode.

detection will be realized in the BESS emulator. As shown in Fig. 6, the islanding detection is realized through the PLL. When abnormal voltage or frequency is detected by the BESS, the BESS emulator will first ride through. After the ride through time, if the abnormal voltage or frequency cannot recover, then the BESS emulator will check whether both the voltage and frequency are abnormal. If both of them are abnormal, the grid loss will be detected and the BESS will send islanding feedback to the MG controller and start the mode transition.

C. Control Functions in the Islanded Mode

1) Voltage Control with Ride Through

As shown in Fig. 7, in the islanded mode, the BESS emulator serves in the grid-forming (GFM) mode to provide the MG with stable voltage and frequency. The voltage is a dual-loop control in *dq* coordinates, where the outer loop is the voltage control to generate the current references and the inner loop is the current loop to regulate the output current based on the generated references. During the fault condition, the BESS emulator also limits its output current to the maximum allowed current. The fault current reference generation also follows (4) while the current references I_d^{Ref} and I_q^{Ref} are generated by the outer voltage loop rather than (3). Once the BESS emulator rides through, the output voltage cannot be maintained, and the MG will be in the low-voltage condition.

2) Primary and Secondary Droop Control

The MG frequency is also established by the BESS emulator in the islanded mode. The frequency regulation is realized through primary and secondary droop control. As shown in Fig. 8, in power grids, if the reactance of the line is much greater than the resistance, the active power can be viewed as coupled with frequency, and the reactive power can be viewed as coupled with voltage [17]. Therefore, in the BESS emulator, the output voltage references are regulated by the reactive power to realize a *Q-V* droop, and the frequency is

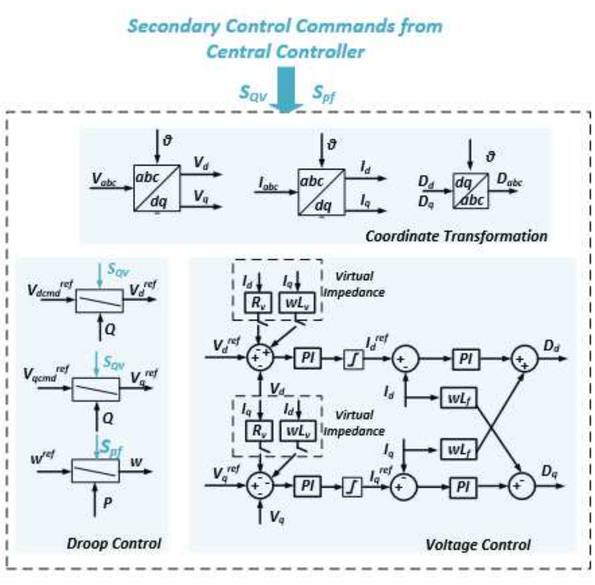


Fig. 7. Control functions in the islanded mode.

controlled by the active power for a *P-f* droop. In addition, *P-f* and *Q-V* droop control can realize the paralleling operation of multiple GFM inverters, which can support the operation of MG with multiple source locations. However, due to the primary droop control, the MG voltage and frequency will be changed with the power of BESS, meaning that the voltage and frequency of the MG may deviate from the targeted value (60 Hz for frequency and 1 p.u. for voltage). To avoid too much deviation, secondary droop control is applied as shown in Fig. 8. The droop curve regulation commands are issued from the MG controller to move the droop curve so that the voltage and frequency can be regulated to the targeted values. The *P-f* and *Q-V* droop equations are:

$$\begin{cases}\omega_t = \omega_0 - k_{Pf}(P_t - P_0) + S_{PF} \\ V_t = V_0 - k_{QV}(Q_t - Q_0) + S_{QV}\end{cases} \tag{5}$$

where ω_t and V_t are the frequency and voltage references, S_{PF} and S_{QV} are the commands from the MG controller.

In the meantime, by applying different secondary control commands, the power distribution among different GFM-controlled BESSs can also be controlled. Moreover, during the reconnection, considering the potential communication delay and mechanical action of switches in HTB [4], the BESS emulator may not be able to switch back to the control in the grid-connected mode when the MG reconnects to the main grid. The GFM-controlled BESS emulator with droop control can operate with the grid temporarily by regulating the BESS voltage and frequency to follow the grid voltage and frequency. If no droop control is applied, the voltage and frequency differences between the BESS emulator and main grid will cause a large inrush current and the reconnection transition cannot be realized.

Therefore, the BESS emulator with both primary and secondary droop control is critical for the MG controller's real-time function (power balancing, MG voltage, and frequency regulation and reconnection) testing.

3) Virtual Impedance Control

The droop control assumes that the line reactance is much greater than line resistance. However, this assumption may not be valid in a MG because the X/R ratio of the MG lines can be small, meaning that the *P-f* and *Q-V* droop relationship may not be accurate in the MG. In order to solve this issue, virtual impedance control is applied to the BESS emulators as shown in

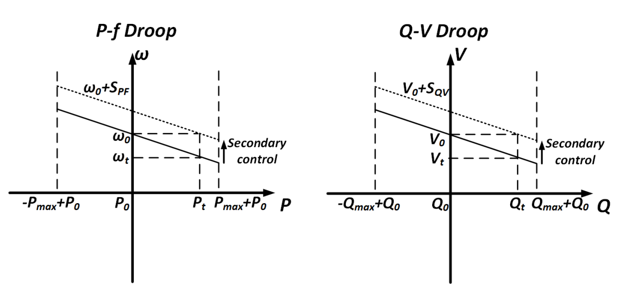


Fig. 8. Primary and secondary droop control.

Fig. 7 [18]. The virtual impedance is designed to be much greater than the line impedances so that the BESS emulator impedance is dominated by the virtual impedances. Therefore, the droop relationship can be met when the virtual reactance is much greater than the virtual resistance.

D. Control Functions During Transitions

During the reconnection transition, the primary and secondary droop control can assist MG controller testing. During the planned islanding transition, since the transition schedule is determined by the MG controller, there is no extra BESS function needed to support the testing. During the unplanned islanding transition, after islanding is detected, the BESS will need to switch to the control in the islanded mode and send mode transition commands to the MG controller. In the steady state, the BESS emulator control mode is determined by the MG controller. Because of the communication delay, before the transition commands arrive at the MG controller, the commands BESSs receive are still for grid-connected mode control, which will impact the unplanned islanding transition.

To solve this issue, a local GFM mode is defined in the BESS emulator during an unplanned islanding transition, which is shown in Fig. 9. During the local grid-forming mode, the BESS emulator still has voltage control with fault ride through, primary droop control, and virtual impedance control. There will be no secondary control. The BESS emulator will not reach the normal GFM mode until the control transition commands from the MG controller are received.

V. EXPERIMENTAL DEMONSTRATION

Experimental verifications are conducted on a HTB shown in Fig. 10, where the MG in Fig. 3 is emulated. The MG parameters are summarized in Table II. The developed BESS emulator is applied for supporting the MG controller HTB testing. The experimental demonstration includes the BESS function demonstration to verify the proposed functions and the selected cases of MG controller testing.

A. BESS Function Verification

1) Sudden Grid Unavailable in Grid-Connected Mode

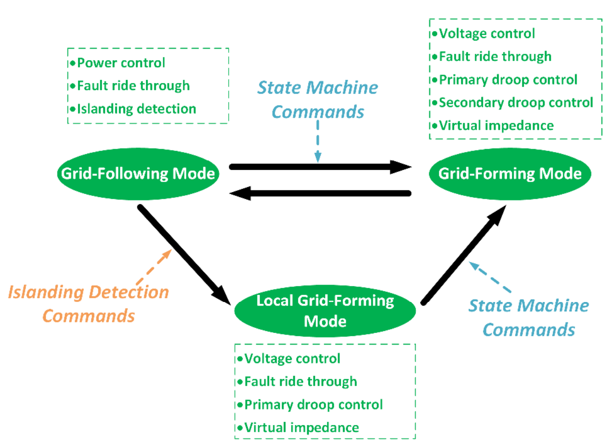


Fig. 9. BESS control during the unplanned islanding transition.

Fig. 10. MG HTB hardware setup.

TABLE II. HTB testing parameters

HTB parameters	Values
Dc-link voltage	200 V
MG voltage (peak)	100 V
Power base	1.732 kW
Line frequency	60 Hz
BESS switching frequency	10 kHz
Inverter parameters	$L_f = 0.575\ mH, R_f = 0.2\ \Omega$

The first testing case is the sudden grid unavailable in the grid-connected mode. In this testing, all the switches in Fig. 3 were closed. Only grid interface, BESS2, and load L3 were enabled. The testing results are shown in Fig. 11. Before the grid was lost, the BESS had been in the GFL mode to control its output power. The grid was suddenly lost at time t_1. The BESS detected the grid loss at time t_2 to enable the local GFM mode to regulate the MG voltage and frequency. During this testing, the MG controller was not involved so the BESS continued to operate in the local GFM mode. This testing can verify the power control in the grid-connected mode, islanding detection and voltage control in the islanded mode.

2) Droop Control with Virtual Impedance

The second testing case is in the islanded mode. The testing results are shown in Fig. 12. Except for S_2, all the switches were closed and the MG worked as a merged island. The load was increased at t_1 and the MG frequency dropped due to the primary droop control of the two BESSs. Then the MG controller issued the secondary droop control commands to two BESSs at t_2 and t_3, respectively, to demonstrate the frequency regulation of two BESSs. The MG frequency was regulated back to 60 Hz after the secondary droop commands had been realized. In addition, in this testing, the virtual impedance control is also implemented so that droop control can be valid for two BESSs. Therefore, this testing can verify the primary and secondary droop control as well as the virtual impedance control in the islanded mode.

3) Fault Ride Through in the Islanded Mode

The third testing case is in the islanded mode. The testing results are shown in Fig. 13. The hardware connection is the

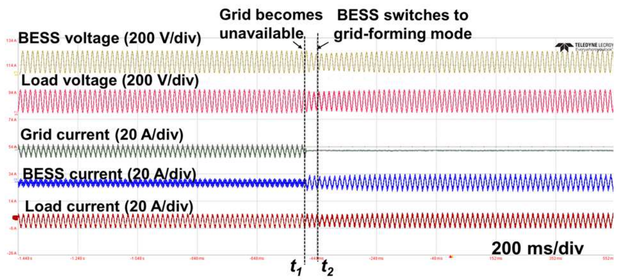
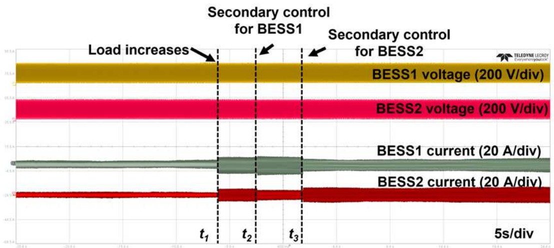
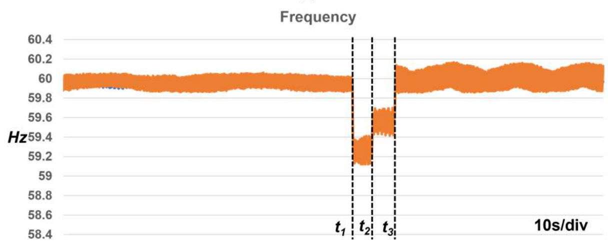


Fig. 11. Sudden grid available in the grid-connected mode.



(a)



(b)

Fig. 12. Testing results of BESS droop control: (a) voltage and current waveforms; (b) frequency waveform.

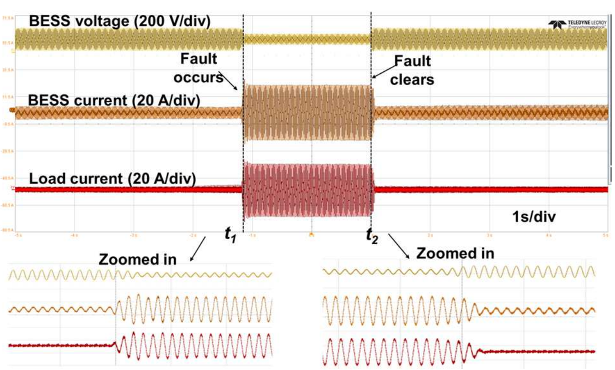


Fig. 13. Testing results of BESS fault ride through in the islanded mode.

same as in the first testing case. During this testing, the load was controlled to be a constant impedance load. A high-impedance fault was emulated by suddenly reducing the load impedance at time t_1, the BESS emulator could not provide all the fault current and started to ride through. The fault was cleared at time t_2. After the fault was cleared, the BESS emulator could recover to the normal operation to continuously support the load. From this testing, the fault ride through capability of the BESS emulator can be verified.

B. *MG Controller Testing Support*

The developed BESS emulator is applied for MG controller function HTB testing. In this paper, the reconnection transition is selected as a representative case for demonstration. The transition process is shown in Fig. 14 where two transition strategies mentioned in section III are realized.

The first strategy is shown in Fig. 14 (a) and the testing results are shown in Fig. 15 (a). At time t_1, two islands merged through switch S_1. After merging, the two BESSs were still operated in GFM mode to support the load in the MG. Then the merged island reconnected to the main grid through switch S_2 at time t_2. At this time, due to the communication delay, the BESS had not received the control transition commands and continued to operate in the GFM mode. The control transition of two BESSs was realized at time t_3 when two BESSs switched operation mode to GFL mode.

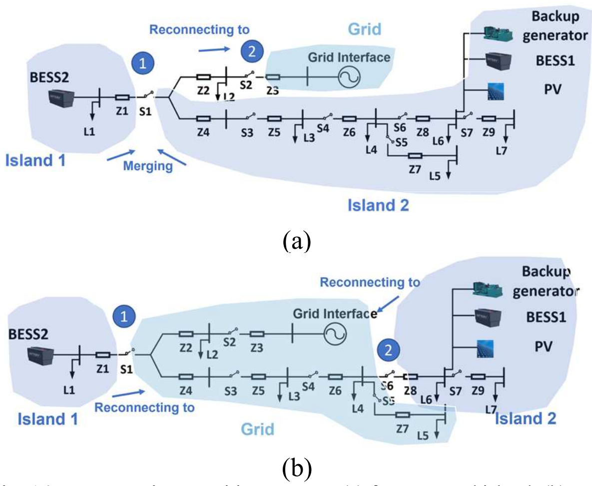
The second strategy is shown in Fig. 14 (b), and the testing results are shown in Fig. 15 (b). At time t_1, island 1 reconnected to the grid through switch S_1. Since the BESS2 had already connected to the grid, it changed its operation mode from GFM to GFL at time t_2. Then island 2 reconnected to the grid through switch S_6 at time t_3 and the BESS control transition was completed at time t_4. For both reconnection strategies, the developed BESS emulators were controlled to regulate the voltage and frequency to assist the resynchronization. Without the modeled control functions (virtual impedance, droop, etc.), the MG controller reconnection transition cannot be realized.

VI. Conclusion

In this paper, a BESS emulator is developed for the controller HTB testing of a MG with dynamic boundary and multiple sources at different locations. The BESS emulator functions are defined from both the MG controller function perspective and the HTB testing perspective.

From the long-time operation perspective, the BESS emulator has the power control function in the grid-connected mode and models the SOC indication for the energy management function. During the steady-state operation, compared with conventional MGs, the targeted MG has more modes in the islanded mode (merged island and separate islands). To support the controller testing, voltage control, primary and secondary droop control as well as virtual impedance control are applied to the BESS emulator. The developed emulator can not only operate in the GFM mode to provide voltage and frequency but also support the paralleling operation of multiple GFM inverters. During the mode transitions, since the MG does not have a fixed point of coupling, the islanding detection is realized in the BESS emulator to support the unplanned islanding testing.

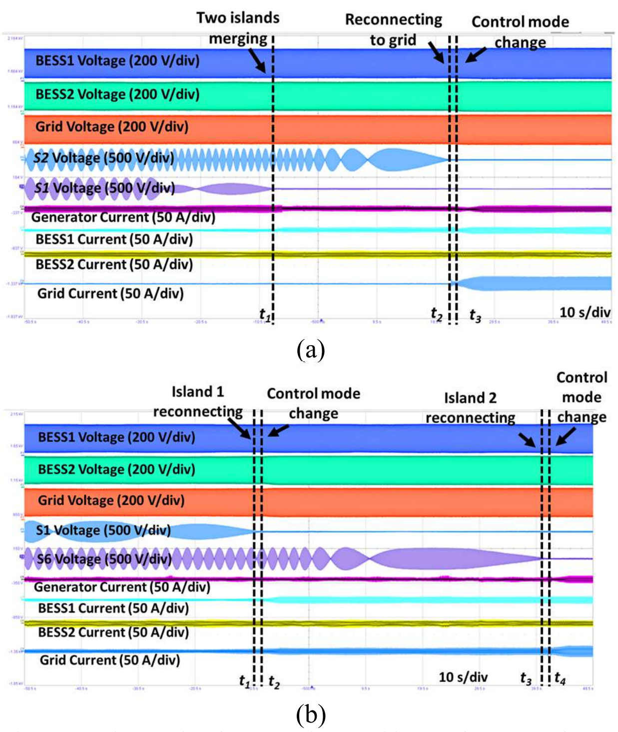
In the meantime, the HTB testing is a practical environment for the MG controller testing by providing communication delays, actual switching actions, etc. Considering the communication delays and mechanical switching actions, the



(a)

(b)

Fig. 14. Reconnection transition process: (a) from merged island; (b) from separate islands.



(a)

(b)

Fig. 15. Testing results of reconnection transition: (a) from merged island; (b) from separate islands.

BESS emulator provides more function for the transitions testing. During the unplanned islanding transition, a local GFM mode is added to avoid the impact of the error command during the delay. Also, for the reconnection transition, during the communication delay, due to the droop and virtual impedance control, the BESSs can temporarily operate with the main grid in GFM mode without causing a large inrush current.

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References

[1] N. Pogaku, M. Prodanovic and T. C. Green, "Modeling, analysis and testing of autonomous operation of an inverter-Based microgrid," *IEEE Trans. Power Electron*., vol. 22, no. 2, pp. 613-625, March 2007.

[2] H. Yin *et al*., "Planned islanding algorithm design based on multiple sub-microgrids with dynamic boundary," *IEEE Open Access Journal of Power and Energy*, vol. 8, pp. 389-398, 2021.

[3] *IEEE standard for the testing of microgrid controllers*, IEEE Standard 2030.8- 2018, Aug. 2018.

[4] D. Li, *et al*., "Development of a converter based microgrid test platform," *in Proc. IEEE Energy Convers. Congr. Exposit. (ECCE)*, Sep. 2019, pp. 6294–6300.

[5] M. Ashourianjozdani, L. A. C. Lopes and P. Pillay, "Power electronic converter based PMSG emulator: A testbed for renewable energy experiments," *IEEE Trans. Ind. Appl*., vol. 54, no. 4, pp. 3626-3636, July-Aug. 2018.

[6] M. T. Lawder, et al., "Battery energy storage system (BESS) and battery management system (BMS) for grid-scale applications," *Proc. IEEE*, vol. 102, no. 6, pp. 1014-1030, June 2014.

[7] J. D. Boles, Y. Ma, J. Wang, D. Osipov, L. M. Tolbert and F. Wang, "Converter-based emulation of battery energy storage systems (BESS) for grid applications," *IEEE Trans. Ind. Appl*., vol. 55, no. 4, pp. 4020-4032, July-Aug. 2019.

[8] H. Zhao, M. Hong, W. Lin, and K. A. Loparo, "Voltage and frequency regulation of microgrid with battery energy storage systems," *IEEE Trans. Smart Grid*, vol. 10, no. 1, pp. 414-424, Jan. 2019.

[9] H. Li, *et al*., "Development of a power electronics-based testbed for a flexible combined heat and power system," *in Proc. IEEE Energy Convers. Congr. Exposit. (ECCE)*, 2021, pp. 764-770.

[10] S. Zhen, et al, "Operation of a flexible dynamic boundary microgrid with multiple islands," *in Proc. IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2019, pp. 548-554.

[11] L. Zhu *et al*., "A smart and flexible microgrid with a low-cost scalable open-source controller," *IEEE Access*, vol. 9, pp. 162214-162230, 2021.

[12] J. Wang et al., "Static and dynamic power system load emulation in a converter-based reconfigurable power grid emulator," *IEEE Trans. Power Electron*., vol. 31, no. 4, pp. 3239-3251, April 2016.

[13] *IEEE standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces*, IEEE Standard 1547-2018, Apr. 2018.

[14] H. Laaksonen, "Advanced islanding detection functionality for future electricity distribution networks," *IEEE Trans. Power Deliv.*, vol. 28, no. 4, pp. 2056-2064, Oct. 2013.

[15] R. Bakhshi-Jafarabadi, J. Sadeh, J. d. J. Chavez and M. Popov, "Two-level islanding detection method for grid-connected photovoltaic system-based microgrid with small non-detection zone," *IEEE Trans. Smart Grid*, vol. 12, no. 2, pp. 1063-1072, March 2021.

[16] M. Seyedi, S. A. Taher, B. Ganji and J. Guerrero, "A hybrid islanding detection method based on the rates of changes in voltage and active power for the multi-inverter systems," *IEEE Trans. Smart Grid*, vol. 12, no. 4, pp. 2800-2811, July 2021.

[17] A. K. Sahoo, K. Mahmud, M. Crittenden, J. Ravishankar, S. Padmanaban and F. Blaabjerg, "Communication-less primary and secondary control in inverter-interfaced AC microgrid: An overview," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 9, no. 5, pp. 5164-5182, Oct. 2021.

[18] H. Zhang, S. Kim, Q. Sun and J. Zhou, "Distributed adaptive virtual impedance control for accurate reactive power sharing based on consensus control in microgrids," *IEEE Trans. Smart Grid*, vol. 8, no. 4, pp. 1749-1761, July 2017.