Design of a Microgrid Transition Controller II: System Recovery Under Abnormal Conditions

Preprint

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National Renewable Energy Laboratory

Presented at the IEEE Power and Energy Society General Meeting
Portland, Oregon
August 5–9, 2018

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Conference Paper
NREL/CP-5D00-70475
August 2018

Contract No. DE-AC36-08GO28308

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***Abstract*—This paper presents a microgrid transition controller for managing emergency operation when the microgrid experiences a system blackout caused by an internal or external fault. The developed transition controller consists of various application function blocks, including normal operation, emergency operation, and coordination between them. The developed microgrid transition controller is validated by a sample microgrid, and two test cases are investigated: islanded black start and grid-connected black start. The simulation results demonstrate the feasibility and effectiveness of the proposed microgrid transition controller for handling emergency operation and transitioning to normal operation.**

***Index Terms*—Microgrid; Emergency Operation; Application Function Block; Black Start.**

I. INTRODUCTION

A microgrid's ability to black start has attracted a lot of attention in recent years because it can rapidly restore the microgrid so that it continues providing uninterrupted power for critical loads under power outages and restore the distribution system if enough cranking power is available from distributed generators [1]. Also, the resiliency of electric grids is significantly improved by optimally managing the operation of a microgrid's assets, such as dispatchable distributed energy resources (DERs) and controllable loads [2].

Therefore, extensive research regarding microgrid black start for distribution system restoration and to maintain critical loads has been performed. Regarding system restoration, a self-healing, resilient distribution system based on sectionalizing into microgrids is developed in [3] to provide continuous, reliable power to the maximum loads. A novel, networked, microgrid-aided approach for system restoration using the spanning tree search approach is presented in [4] to maximize the restored loads. An evaluation of a microgrid's black-start capability and schemes is presented in [5] considering possible benefits and associated technical challenges. For a microgrid black start to support critical loads, an optimal black-start functionality procedure based on mathematical optimization is developed in [6] to achieve reliable black-start schemes. Generalized rules for microgrid black-start operation are proposed in [7] to restore critical loads as quickly as possible.

Significant progress has been made in these particular areas of research for microgrid black-start capabilities, but the capability to support critical loads needs more attention. Most of the existing literature treats a microgrid's black start as a single operation, and great efforts are made to develop sophisticated optimization algorithms; however, from the point of view of microgrid operation, black-start operation is also an operation mode—i.e., an emergency mode—similar to other operation modes, such as grid-connected, islanded, and transitioning between them. A complete microgrid control system should include the control and management of all different modes and the coordination among them. For instance, black-start functionality should override all other operation functionalities when system blackout and collapse occur. When the microgrid's black start (self-start) is successfully performed, the islanded operation functionality should take control of the microgrid, then the black-start functionality will be running in the background. Reference [8] proposes conceptual coordination schematics for all of the microgrid's operation modes. A microgrid controller that manages the operation and control of the microgrid under normal conditions (grid-connected, islanded, and the transition between them) is developed in [9]. This paper aims to continue the research in [9] by developing a microgrid transition controller that performs a black start under abnormal conditions (e.g., natural disaster, system collapse) with the objective of powering critical loads. As an extension of [8] and [9], the developed microgrid transition control system includes the application function blocks (AFBs) for black start, and we focus on the black start operation and coordination of black-start functionality with other operation functionalities. In consideration of the computation burden on the microgrid central controller, a predefined sequence of actions for black start is inserted in the AFB for black-start operation mode rather than embedding a mathematical optimization algorithm. The developed microgrid transition controller will be tested via simulation of a sample microgrid that targets providing continuous power supply for critical loads.

II. OVERVIEW OF MICROGRID OPERATON

Fig. 1 presents a flowchart of microgrid operation under different conditions. In normal conditions, the microgrid system operates in any mode inside the inner loop, which is comprised of the operation modes in the green boxes, purple diamonds, and purple boxes. The focus of this paper is on abnormal conditions, so the details of the operation process for normal conditions will not be discussed here but can be found in [8]. In this paper, abnormal operation is called emergency operation mode, and it is in the outer loop of the flowchart. The emergency operation mode is complex and might be caused by main grid or microgrid faults, unscheduled outages, or voltage and/or frequency transients. Some microgrid control systems can detect these unexpected

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory.

conditions and transition to a stable islanded operation mode. In most cases, however, the microgrid transitions to an unstable system or black-out collapse.

When a microgrid black-out occurs, the microgrid system enters emergency operation mode. In this mode, two functions are included: (1) the decision on black-start option−grid-connected or islanded, based on the conditions of the microgrid assets and availability of the main grid; and (2) the sequence of actions. If the microgrid decides on an islanded black start option, the green box for islanded operation mode will be selected, and the microgrid system will restart the master asset first, reenergize the transformer and lines, and then connect critical loads, etc. Once the microgrid system is stabilized in islanded mode and the main grid is ready, a reconnection signal might be sent from the distribution network operator (DNO) to the microgrid central controller. Then the microgrid is on the path to normal grid-connected operation and will transition from reconnection control and check (marked by the purple diamond), to grid-connected operation (marked by the purple box), and to grid-connected mode (marked by the green box). Alternatively, the microgrid can choose to black start via connecting to the main grid first−once the main grid conditions are restored to normal, reenergize the transformer and line, and reconnect the critical loads. This work considers only the microgrid's black start (either islanded or grid-connected). The situation in which the microgrid black starts and restores the distribution system will be included in future work.

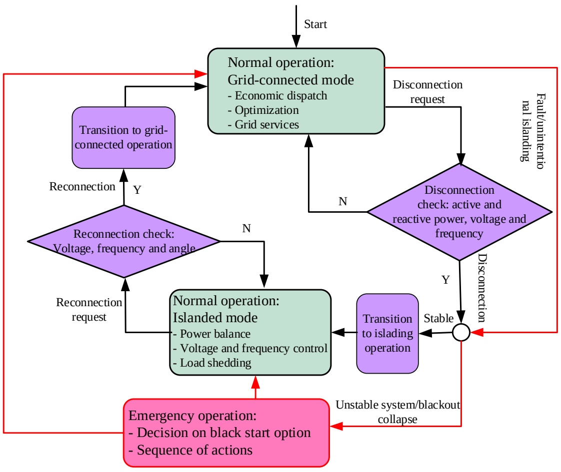

Fig. 1. Overview of microgrid operation under different conditions.

III. Design of the Microgrid Transition Controller for Black Start

Fig. 2 presents the schematic diagram of a microgrid transition controller. As shown, the microgrid transition receives a command from the DNO control room and feeds back the status of the microgrid's operation. Based on the command from the DNO, network conditions, and measurements, the microgrid operates in any of the operation modes. The output signals from the microgrid transition controller are control commands and control references, which are sent to the device-control level for execution. At the field level, the microgrid assets receive the final command from the device-level controller and execute the command.

The microgrid transition controller includes nine AFBs that are located in the supervisory level (microgrid central controller). The AFBs in steady-state and transition-state operations are enabled-based and run only if the enable conditions are satisfied. But the sub-AFB for detection of black out conditions within the emergency operation mode (AFB#8) will operate all the time. Based on the voltage and current measurements at the point of common coupling (PCC), the blackout/system collapse status will be detected. If these conditions are not detected, this sub-AFB will not trigger the other sub-AFBs (the decision on black start option, sequence of actions, and end of black start) inside AFB#8, and it will send the status signal to AFB#1 (operation-mode management) to inform it of the "normal" status of the system. Otherwise, once the detection of a black start is "true," the sub-AFBs inside AFB#8 will be enabled to decide the black start option and then generate the sequence of actions. At the same time, the operation mode management (AFB#1) will get notified immediately, and it will disable the AFBs for steady state and transition state accordingly. The operation mode selection signal will change to the value that chooses AFB#8, and AFB#9 (control signal generation) will output the control command and references generated by AFB#8 to black start the microgrid. If the black start is successfully achieved, the end of black start sub-AFB will send a status signal to the detection of black start sub-AFB, then the other three sub-AFBs inside AFB#8 will be disabled. Also, AFB#1 will be informed of the success of the black start, and the microgrid operation mode will be updated to a normal condition – either grid-connected or islanded.

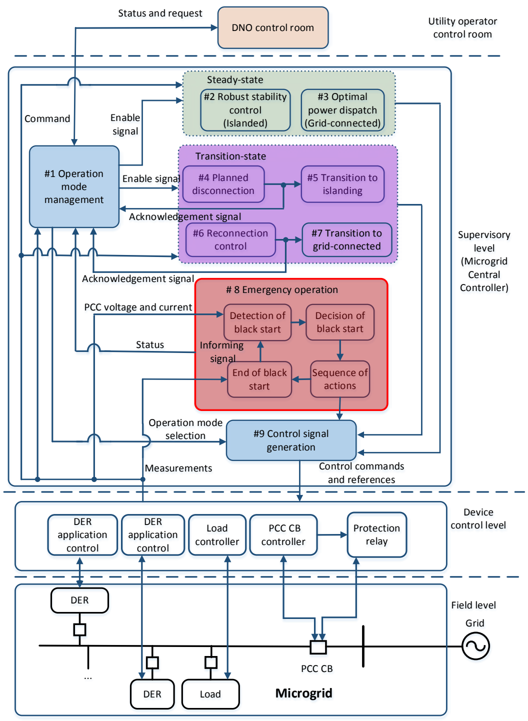

Fig. 2. Schematic diagram of the microgrid transition controller.

IV. Implementation of the AFBs for Emergency Operation

This section presents the detailed implementation of AFB#8. This paper is an extension of [9], and that paper presents details on AFB#2 – AFB#7 and AFB#1 for normal operation modes. Since AFB#1 includes additional signals to implement emergency operation, we present it here again to give a good understanding of how emergency operation mode coordinates with other modes.

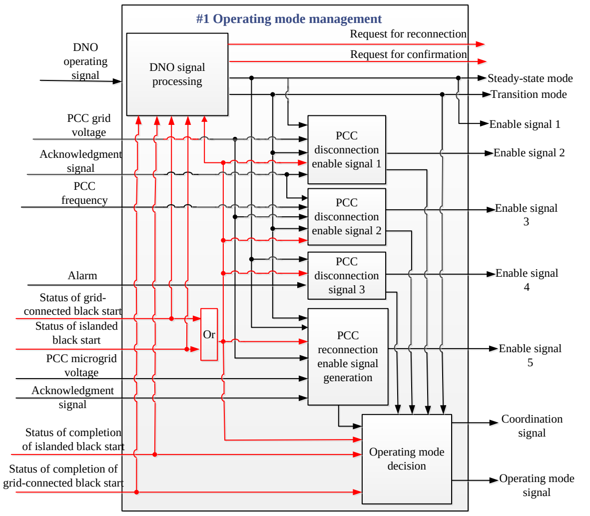

Fig. 3. Schematic diagram of AFB#1, operation-mode management.

Fig. 3 shows the schematic diagram of AFB#1 with the additional signals required to support emergency operation marked in red. The inputs from AFB#8 are the status of grid-connected black start, status of islanded black start, status of completion of grid-connected black start and status of completion of islanded black start. If either the status of grid-connected black start or the status of islanded black start is "true", the steady-state operation and transition-state operation modes will be disabled and stop running their algorithms and the operation mode decision will switch to emergency operation and the output of the AFB#8 will be sent through AFB #9 to generate control references to the device control layer. If the black start is grid-connected, AFB#1 sends a request to the DNO for confirmation and the confirmation from the DNO is sent to AFB #8, then AFB #8 manages the black start. Once the black start is completed, the sub-function block "operating mode decision" will change the operation mode of the microgrid according to the network conditions. For example, if the microgrid performed grid-connected black start successfully and operates stably for predefined time, then the microgrid will change to the grid-connected mode and the algorithm for this mode (optimal power dispatch, AFB #1) will be enabled. If the microgrid performed islanded black start successfully and operates stably for predefined time, then AFB#1 will send a request to the DNO for reconnection, and the reconnection control (AFB #6) operation will be performed if the DNO agrees.

Fig. 4 shows the schematic diagram of AFB#8, emergency operation. It starts from the first sub-AFB#8.1, detection of blackout, which uses the information from the PCC grid-side voltage, PCC microgrid-side voltage, and value of steady-state mode (from AFB#1). Each variable has two states: "0" and "1." If the voltage is normal, the state value is "1", so there are eight combinations: two conditions resulting in microgrid islanded black start, one condition resulting in grid-connected black start, and five resulting in no black start. Based on this derivation, we have the implementation of sub-AFB#8.1.

If the black start option is islanded, the sub-AFB#8.2 (decision of black start option) will trigger islanded black start in sub-AFB#8.3 immediately. Otherwise, if it is grid-connected, we need to wait for confirmation from the DNO and only then launch the grid-connected black start. If no confirmation is received, the islanded black start will be launched. The outputs of sub-AFB #8.3 (control commands and references) will be sent to AFB#9, which will function as control signal generation to send all control signals to the device level and/or field level for execution. Sub-AFB#8.4 will check whether the black start is completed based on the measurements. If black start is completed successfully, a status signal indicating the successful completion of the black start will be sent to sub-AFB#8.2 and from there to AFB#1. Once sub-AFB #8.2 receives this signal, it will stop enabling sub-AFB #8.3 and sub-AFB#8.4. At the same time, AFB#1 will modify the operation mode of the microgrid. In Fig. 4, the red arrows indicate the input and output signals.

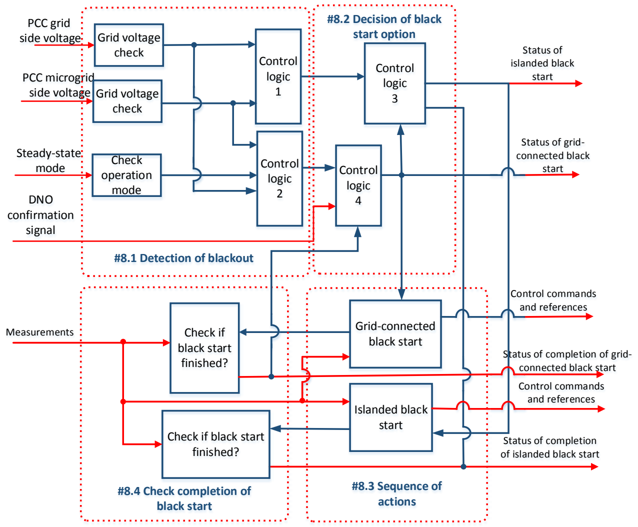

Fig. 4. Schematic diagram of AFB#8, emergency operation.

A more detailed implementation of sub-AFB#8.3 is presented here. For the sequence of actions in islanded black start, refer to [1]. It lists the sequence as: disconnection of all loads, building the low-voltage network, synchronizing small islands, connecting controllable loads to the low-voltage network, connecting non-controllable DERs or DERs without black-start capability, increasing the load, and changing the control scheme of the inverters and microgrid synchronization with the medium-voltage network. The sequence of actions for grid-connected black start is slightly different from that for islanded black start because there is no need to build up the low-voltage network by using a DER with black-start capability. Critical loads are usually connected first after PCC circuit breaker is closed.

V. Simulation Results for Black Start Using a Sample Microgrid

The proposed microgrid transition controller offers an automatic solution to manage the normal and emergency operation of a microgrid. The validation of the controller under normal operation is presented in [9], so this section presents only the validation of the microgrid controller under emergency operation in a sample microgrid to demonstrate its feasibility and effectiveness. This microgrid has 2 Batteries, 2 PV, 3 critical loads and some noncritical loads. One battery with 300 kW rated power is the black start source. The configuration of the sample microgrid and parameters can be found in [9].

Two scenarios are investigated in this section. Scenario 1: the microgrid experiences a blackout caused by an external fault, and islanded black start is launched. Scenario 2: The microgrid experiences a blackout in islanded operation caused by an internal fault, and grid-connected black start is initialized. This section presents results on the coordination signals of the microgrid transition controller and measurements of the microgrid (such as PCC voltage and frequency, and critical loads circuit break status) to show the microgrid's emergency operation. The performance of the proposed microgrid transition controller for emergency operation is evaluated assuming that the communications among different control layers are working well.

A. Scenario1: Islanded Black Start

In this scenario, the microgrid system starts from operating in grid-connected mode. Then an external fault is triggered and removed after a certain amount of time. The microgrid controller detects the blackout and black starts the microgrid in islanded mode. Once islanded black start is completed, the controller sends a request for reconnection and after confirmation is received from the DNO, it performs resynchronization and then operates in grid-connected mode.

Fig. 5 shows the operation of the microgrid and coordination signals inside the microgrid transition controller. As shown, the external fault is applied at 3 s and cleared at 4 s, and the relay at PCC circuit breaker detects the microgrid's dead bus within 40 ms. The microgrid transition controller detects the blackout at 3.06 s and informs the DNO. The signal from DNO (the 3rd signal in Fig. 5) is informed about the microgrid's blackout status, so the operation command changes to islanded operation at 3.1 s after the notice. The microgrid transition controller decides to launch islanded black start at 3.06 s, and it finishes the self-black-start process at approximately 12.7 s. Once the black start is completed, the output of the black-start completion block is "high" to indicate that the black start is finished, and it holds the "high" status for a few seconds. Then a request for reconnection to the main grid is sent to the DNO at 15.2 s, and this request is confirmed by the DNO at 17.5 s (indicated when the DNO signal changes from "0" to "2" and the microgrid needs to complete resynchronization before 20.5 s).

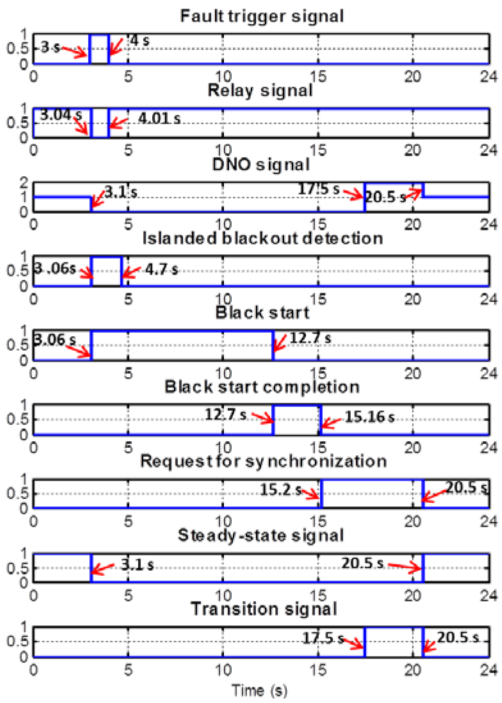

Fig. 5. Coordination signals inside the microgrid transition controller for islanded black start.

The DNO signal "0" means islanded mode, "1" means grid-connected mode and "2" means transition from islanded to grid-connected mode. The microgrid is requested by the DNO to operate in grid-connected mode after 20.5 s. The translated steady-state signal and transition signal also validate the microgrid's operation: before the blackout is detected, the microgrid is requested by DNO to operate in grid-connected mode (the "steady state" is "1" before 3.1 s); grid-connected mode is allowed only after synchronization is completed ("steady-state" is "1" again after 20.5 s); the microgrid operates in black-start mode between 3.06 s and 12.7 s (black start is "1" during this time, and it disables all other operation functionalities) and switches to islanded mode between 12.7 s and 17.5 s ("steady-state" is "0" during this time); resynchronization is launched during 17.5 s and 20.5 s ("transition signal" is "1" during this time). All the results shown in Fig. 5 demonstrate the correct functioning of the microgrid transition controller and the correct coordination and timing among different operation functionalities.

Fig. 6 shows the measurements at the PCC to further validate the performance of the proposed microgrid transition controller for emergency operation. The PCC circuit breaker status shows that the microgrid is connected to the grid before 3.04 s, disconnects from the main grid at 3.04 s, and reconnects back to the main grid at 18.6 s. The PCC microgrid voltage and frequency show that the microgrid blackout occurs from 3.02 s to 4.68 s, and it recovered rapidly to normal operation after the black start is launched. Note that 20 ms after the fault is applied due to the time delay introduced by the low pass filter used to calculate the voltage and frequency. The magnified view of voltage and frequency shows that the microgrid controller is able to successfully reestablish voltage and frequency within acceptable limits. The PCC active and reactive powers show the correct operation of the microgrid.

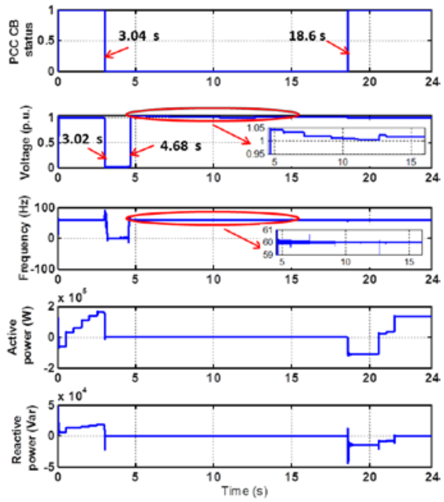

Fig. 6. Measurements at the PCC: PCC circuit breaker status, voltage, frequency, active and reactive power.

Fig. 7 shows the active and reactive power of the black-start source – the battery – and the status of the circuit breakers for the critical loads. The BESS is shut off when the blackout is detected, and it is the first asset to be connected back to energize the low-voltage microgrid. Once the microgrid is re-energized, the most critical load (Load 1) is reconnected, the second critical load (Load 2) is reconnected after a certain amount of time, and the third critical load (Load 3) is reconnected as well. Fig. 7 demonstrates that all critical loads are served in a very short time.

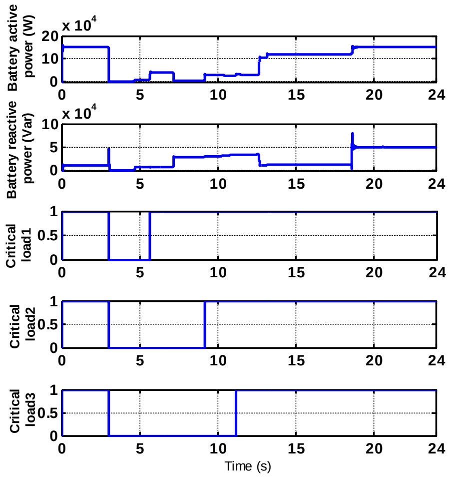

Fig. 7. Results of the assests: active and reactive power output of the black-start source and the circuit breaker status of the critical loads.

B. *Scenario 2: Grid-Connected Black Start*

In this scenario, the microgrid system starts from operating in islanded mode. Then an internal fault is triggered and removed after a certain amount of time. The microgrid controller detects the blackout and black starts the microgrid in grid-connected mode (a request signal is sent to DNO, wait for DNO confirmation and black start is lunched). Once the grid-connected black start is completed, the microgrid controller transfers the operation mode to grid-connected operation.

The results in this scenario are similar to the results shown in Scenario 1. The coordination signals demonstrate the correct function of the microgrid transition controller to manage the grid-connected black start and also the correct coordination and timing among different operation functionalities. Results of the assets (main DER source and critical loads) shows that critical loads and the main DER source are powered one by one based on the defined timing and operation procedures.

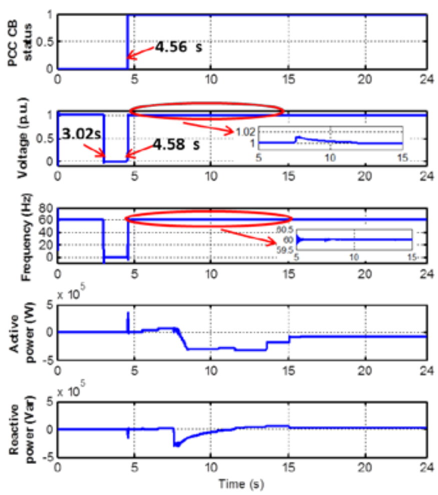

Fig. 8. Measurements at the PCC: PCC circuit breaker status, voltage, frequency, active and reactive power.

Fig. 8 shows the measurements at the PCC to illustrate the grid-connected black start. The PCC circuit breaker status shows that the microgrid is connected to the grid at 4.56 s. The PCC microgrid voltage and frequency show that the microgrid is in blackout from 3.02 s to 4.58 s, and it recovers rapidly to normal operation after black start is launched. The magnified view of voltage and frequency shows that the microgrid controller is able to successfully reestablish voltage and frequency within acceptable limits during the black-start process. The PCC active and reactive powers show the correct operation of the microgrid.

The results here are in line with the designed operation procedures of grid-connected black start.

VI. Conclusions

This paper presents a microgrid transition controller for managing emergency operation when the microgrid experiences a system blackout caused by an internal or external fault. The proposed transition controller consists of various AFBs that include the operation functionalities for normal operation, emergency operation, and coordination between them. The focus is on the AFBs for operation mode coordination and emergency operation. The proposed microgrid transition controller for emergency operation is validated by using a sample microgrid with two test cases. The contributions of the paper are summarized as: 1) The proposed microgrid transition controller provides a design framework and microgrid automation solution for researchers and engineers working in the microgrid controller design area. 2) The simulation results demonstrate the feasibility and effectiveness of the proposed microgrid transition controller for handling emergency operation and transitioning to normal operation.

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