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Design and Development of a Sequence of Operation for Utility Microgrids

**N. GURUNG, R. SHARMA, H. CHEN,
H. ZHENG**
Commonwealth Edison Company
USA

O. ALIZADEH
Quanta Technology
Canada

SUMMARY

This paper presents a methodology to develop a sequence of operation (SOO) for utility-operated microgrids. In general, microgrids can operate in grid connected mode or islanded mode. However, they can have diverse operating modes depending on their location, design, available resources, and overall objective. This paper describes generic steps in developing an SOO that can be applied to microgrids of various sizes as well as diverse configurations. As the adoption of microgrids increase and concepts of networked microgrids continue to evolve, the specifications described in this paper can facilitate standardization and integration of microgrids into the electric grid. The SOO is implemented on a microgrid master controller (MMC) that defines various functionalities including seamless transition of a microgrid from one mode to another, and dispatch of microgrid resources to ensure safe, economic and reliable power to the customers.

KEYWORDS

Distributed Energy Resources, Microgrid, Sequence of Operation

I. INTRODUCTION

As utilities work to improve the reliability and resiliency of the distribution grid and integrate more renewable energy resources into the electric systems, microgrids have emerged as one of the most effective solutions. Microgrids can decentralize energy supply, incorporate clean energy resources, and enhance power system reliability and resiliency [1]-[5]. Microgrids can consist of a variety of components including critical and non-critical loads, distributed energy resources (DERs) such as solar photovoltaic (PV) and battery storage systems, and a wide range of controllable distribution assets. Microgrids are also capable of operating in isolation from the utility grid during disturbance or extreme weather events. They also operate and transition to other several modes such as load transfer and clustering. The capability of various operating modes and the smooth transitions between these modes ensure power supply to critical loads and infrastructure with higher reliability [6]. A utility-operated microgrid is typically defined as a microgrid that is operated by utility and consists of one or more distribution feeders (or a portion of the distribution feeders) with their point(s) of interconnection (POI) at the medium voltage level.

A microgrid goes through a sequence of operation (SOO) events during transition from one operating mode to another. Appropriate plan, design, and development of SOO is needed for smooth transitions, protection, and reliable operation of the microgrid [7]-[8]. This paper presents a step-by-step methodology to develop an SOO for utility-operated microgrids. Although specifying an exact SOO for a target microgrid may not be realized without knowing the type of microgrid and its configuration, it is possible to describe generic steps in developing an SOO that is applicable to most utility-operated microgrids. These specifications can facilitate standardization and integration of microgrids into the distribution grid. To provide an example for the application of the presented methodology, an example microgrid configuration is introduced in this paper, and the SOO is developed for this microgrid by following the proposed methodology.

In section II, a methodology is presented to develop an SOO for utility-operated microgrids. In section III, the methodology is used to develop the SOO for an example microgrid configuration.

II. METHODOLOGY FOR DEVELOPMENT OF SEQUENCE OF OPERATION FOR UTILITY MICROGRIDS

A. Determine Microgrid's Operating Modes and Mode Transitions

The first step in developing an SOO for a utility-operated microgrid is to determine the required modes of operation that the microgrid can operate in safely and reliably, as well as the corresponding mode transitions. To further assess the performance of a microgrid during the required transitions, success criteria and metrics (such as time to reach the steady state after the transition starts with an operator command or following an unplanned incident) can be developed for each of the transitional conditions.

At the very least, a microgrid should be able to operate in an islanded mode or grid connected mode if connection to utility grid is available. However, there can be multiple possible modes of operation depending on the microgrid configuration, location, and control objectives. Following operating modes and mode transitions can be considered for a utility-operated microgrid:

Normal/Grid Connected mode: In this operating mode, the POI switch/es is/are closed, and feeder/s within the microgrid boundary is/are energized through the main utility grid. Hence, DERs are typically set in grid-following control mode and may be required to support the grid voltage and frequency per interconnection requirements set by the host utility. The DERs may be dispatched via microgrid master controller (MMC) to optimize the cost of consumption or

carbon reduction. In a utility operated microgrid, some DER operators may be allowed to dispatch independently per their best interest. In a radial configuration, if the microgrid consists of more than one feeder, with each feeder having a separate POI with the main utility grid, the tie-switches between the feeders are maintained open during normal mode.

Load transfer mode: Load transfer modes can be defined for a microgrid, if it consists of more than one feeder connected via tie-switches, with each feeder having a separate POI with the main utility grid. For example, if there are two feeders, say feeder 1 and 2, within the microgrid (as shown in Fig. 1) and connected via a tie-switch, transfer 1 mode can be defined when the load on feeder 1 is transferred to feeder 2 by closing the tie switch and opening the POI of feeder 1. Similarly, transfer 2 mode can be defined when the load on feeder 2 is transferred to feeder 1 by closing the tie switch and opening the POI for feeder 2.

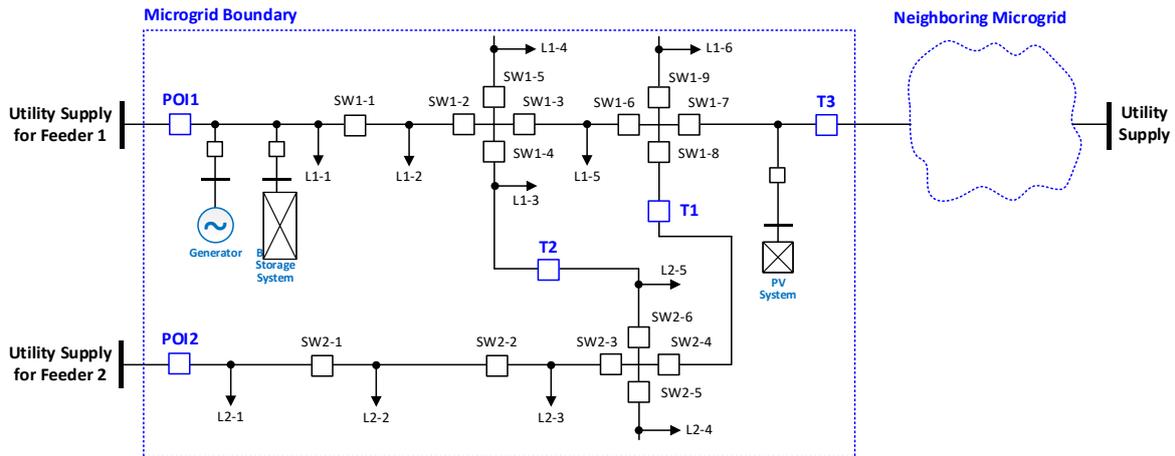


Fig. 1. Single line diagram of an example microgrid configuration

Islanded mode: In this operation mode, the microgrid is disconnected from the main utility grid. A grid-forming source should be available and connected within the microgrid to enable this mode of operation. Islanding can be partial or full depending on the configuration of the microgrid. If the microgrid consists of more than one feeder, with each feeder having a separate POI with the main utility grid, each feeder with a grid forming generator can potentially isolate from the main grid and the rest of the microgrid feeders to form a partial island. If all the feeders within the microgrid boundary get isolated from the main grid with their tie breakers closed, it is considered to be in full island mode.

Clustering mode: Clustering mode can be formed when an islanded microgrid is tied to one or more neighboring microgrids that are also operating in islanded mode to enhance overall reliability and optimize available resources. If a cluster is formed by closing the tie breaker between two microgrids, one microgrid may act as the grid-forming microgrid while the resources in the other microgrid can be switched to grid-following or droop control mode. This holds true for any cluster of more than two microgrids. It requires coordination between the microgrid master controllers of the microgrids to ensure transition of microgrids to clustered mode and continued operation in this mode.

Blackout (power off) status: Blackout condition occurs when the microgrid encounters an unexpected outage of grid or grid-forming resources or is intentionally powered off for safety reasons. The generation resources are shut down and loads are disconnected in this mode.

Black start and load restoration: Black start is the process of powering up the generators and the loads after a blackout. Black start operation includes starting up a grid-forming resource within the microgrid to restore power to the microgrid customers in a sequential manner. Additional generation resources in grid-following control mode can also be connected in the microgrid to further support the load.

In addition to these different modes of operation, the possible transitions from one mode to other modes should be clearly identified and defined during the planning phase. Some of the common transition modes are discussed in this section.

Planned islanding transition: Planned islanding is defined as the transition from normal mode of operation to island mode under a planned scenario. The transition may result in partial or full islanding if the microgrid consists of two or more feeders with separate POIs. During the transition, the microgrid operator reduces the power flow at POI(s) to a value near zero and opens the POI switch/es, thereby isolating the microgrid from the main grid. One of the generation resources, typically the largest unit that can be dispatched, should be capable of switching from grid-following control mode (in normal mode of operation) to grid-forming control mode, upon transition to islanding mode.

Unplanned islanding transition: Unplanned islanding is defined as the transition from normal mode of operation to islanding mode under a contingency condition, typically after a loss of power in the upstream. Microgrid configurations always transitions into partial islanding mode if unplanned islanding is successful, as the microgrid generation can seamlessly transition to grid-forming control mode to continue supplying the load in the partial island. A threshold may exist for the mismatch between microgrid load and generation for a successful seamless transition following an unplanned islanding incident. Above this threshold, the microgrid may not be capable of seamless islanding and will experience an outage.

Transition from partial islanding to load transfer mode: If the microgrid consists of more than one feeder with separate POIs, when the microgrid is partially islanded, the operator can transfer the load of the isolated microgrid feeder to another healthy feeder within the microgrid boundary. This is performed by closing a tie switch between the two feeders. Before the tie switch is closed, the islanded feeder should be in synchronization with the healthy feeder.

Resynchronization and reconnection: Resynchronization and reconnection process are performed to transition the microgrid from islanding mode back to grid-connected mode. Before closing the POI, the microgrid voltage at the POI should be synchronized to the grid voltage on the other side of the POI. After successful reconnection of the microgrid to the main utility grid, all the generation resources in the microgrid should be in grid-following or droop mode.

B. Develop High-Level Diagram of Operating Mode Transitions

Once the proper operating modes are determined, the microgrid should be able to operate in these modes and transition from one to another, depending on the system conditions and operator decisions. As the first step in developing the microgrid SOOs, a high-level diagram of its operating mode transitions can be developed. The various operation modes indicated in the diagram can be color-coded as elaborated below:

- Blue: Indicating operating modes related to the default operation including functions performed by the microgrid under normal condition, such as economic dispatch, peak shaving, renewable firming, etc.
- Yellow: Indicating operating modes related to planned events that are fully navigated by the operator.
- Red: Indicating operating modes when a contingency forces the microgrid transitioning from existing mode of operation to another mode, and are typically a function of microgrid controller to perform the transition upon identifying the contingency.

C. Develop Overall Process Flowchart

In this step, the overall process flowchart is developed based on the high-level diagram. The overall process flowchart incorporates details on the sequence of events for mode transitions. For example, it includes the steps for verification of a successful transition, steps to be executed

following an unsuccessful transition and how the active operating modes of the microgrid should be changed by the microgrid controller. The overall process flowchart along with the sub-processes (described in the next section) can be used in the microgrid controller to implement the SOO.

D. Develop Sub-Process Flowcharts

As the last step for developing the SOO, each of the sub-processes introduced in the overall process flowchart are described in detail. The sub-processes include detailed instructions on monitoring and control of different assets within the microgrid to achieve the required functions and sequence of switching. When the execution of each sub-process is completed, it should return either as a successful operation message or as an alarm that indicate the required steps within the process were not completed successfully.

III. DEVELOPING SEQUENCE OF OPERATION FOR AN EXAMPLE MICROGRID CONFIGURATION

In this section, the development of the SOO for an example utility microgrid is explained by following the steps described in Section II.

A. An Example Microgrid Configuration

Fig. 1 illustrates the single line diagram of an example microgrid configuration consisting of two feeders (feeder 1 and feeder 2) with separate POIs (POI1 and POI2) that connect each feeder to different locations on the main utility grid. The feeders can also be tied together at two separate locations using tie switches T1 and T2. There are multiple switches along the feeders which can be remotely controlled by the microgrid controller or system operator. The example microgrid has a generator (equipped with grid-forming and grid-following control modes and capable of switching between the two), a battery storage system, and a solar photovoltaic (PV) plant. These resources can receive control setpoints from the microgrid controller/system operator.

B. Microgrid's Operating Modes

Table 1 shows the different operating modes considered for the example microgrid as well as the status of main switches within the microgrid under each operating mode.

TABLE 1. STATUS OF MAIN SWITCHES UNDER DIFFERENT OPERATING MODES OF THE EXAMPLE MICROGRID CONFIGURATION

Operating Mode	Status of Switches				Remarks
	POI1	POI2	T1 (or T2)	T3	
Normal	C	C	O	O	
Load Transfer 1	O	C	C	O	Load on feeder 1 is transferred to feeder 2 using tie switch T1 (or alternatively, by using tie switch T2)
Load Transfer 2	C	O	C	O	Load on feeder 2 is transferred to feeder 1 using tie switch T1 (or alternatively, by using tie switch T2)
Partial Island	O	C	O	O	Isolation of feeder 1 from the grid using the grid-forming generator connected to the feeder
Full Island	O	O	C	O	Full isolation of both feeders from the grid using tie switch T1 (or alternatively, by using tie switch T2) and using the grid-forming generator connected to feeder 1
Partial Cluster	O	C	O	C	Cluster of the partial island (i.e., isolated feeder 1) with the neighboring microgrid using the tie switch T3
Full Cluster	O	O	C	C	Cluster of the full island with the neighboring microgrid using the tie switch T3

Note: C: Closed switch, O: Open switch

C. High-Level Diagram of Operating Mode Transitions

Fig. 2 illustrates the high-level diagram of operating mode transitions for the example microgrid configuration based on the color codes described in section II.B.

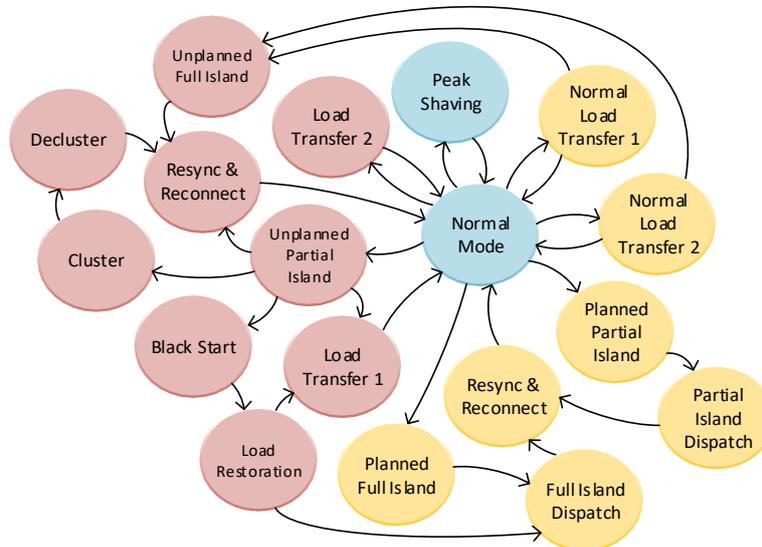


Fig. 2. High-level diagram of operating mode transitions for the example microgrid configuration

D. Develop Overall Process Flowchart

Fig. 3 illustrates the overall process flowchart which is developed based on the description in Section II.C. As shown in the **Error! Reference source not found.**, the blocks in the flowchart include:

- Automatic actions, such as verifying if the operator requested any change in the microgrid operating mode or whether an executed transition process has been completed successfully,
- Sub-process blocks, where a transition scenario (as explained in Section II.A) is executed,
- Operating mode status blocks, where the active operating mode is changed to the last successfully executed mode.

E. Develop Sub-Process Flowcharts

To provide an example of a sub-process flowchart, Fig. 4 illustrates the ‘planned partial islanding’ sub-process for the example microgrid configuration. In this partial planned islanding process, the POI1 is opened to isolate the upper subsystem in Fig. 1 from the main utility grid. This flowchart in Fig. 4 shows the microgrid’s sequence of operation that starts when called upon in the overall process flowchart and ends when either of the following:

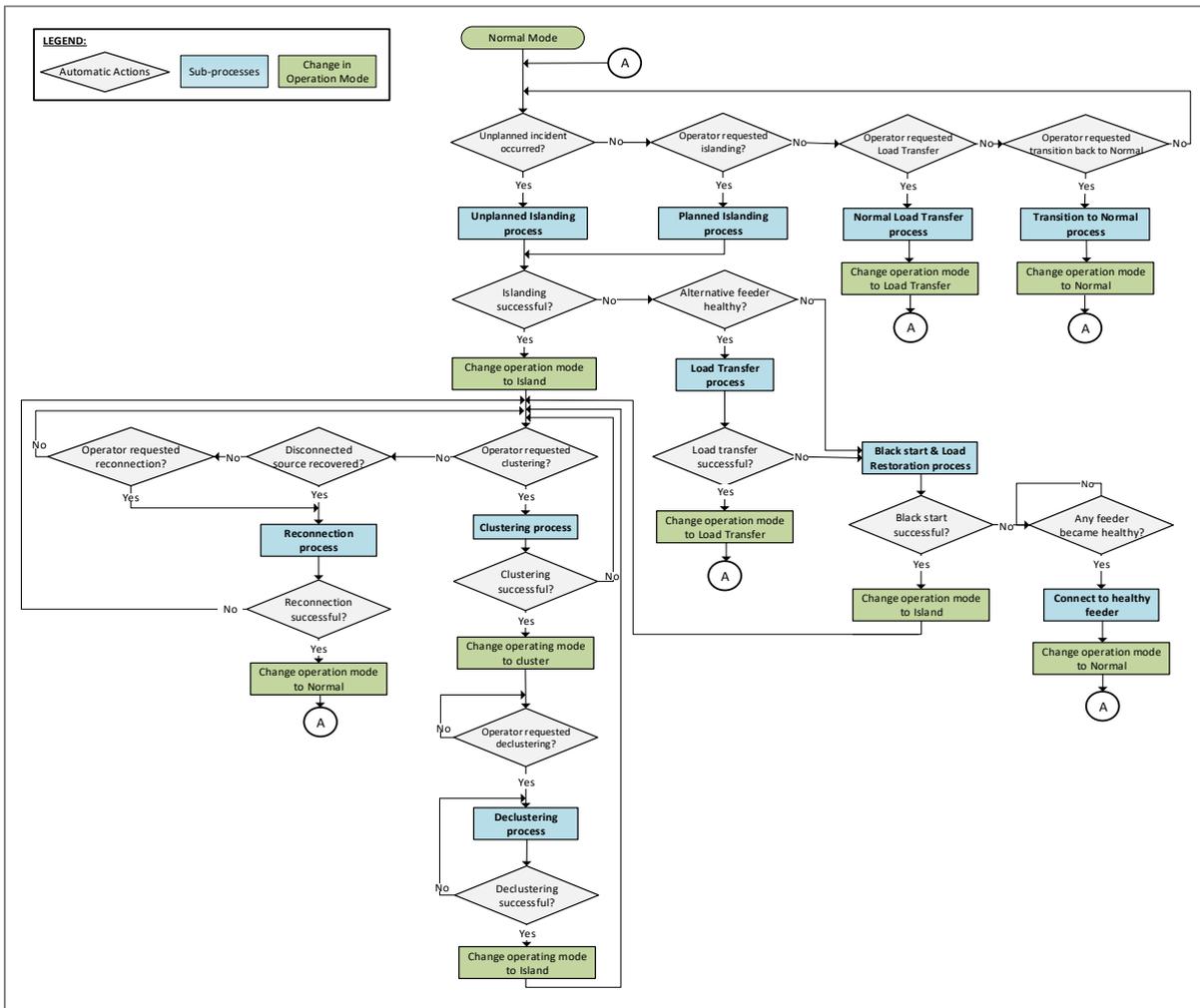


Fig. 3. Overall process flowchart for the example microgrid configuration

- The sub-process returns ‘partial islanding was successful’: All the steps within the sub-process are executed and completed successfully and the program returns to the overall process flowchart.
- The sub-process returns an alarm indicating that ‘partial islanding was NOT successful’: The command from the microgrid controller to open switch POI1 has failed and hence partial islanding has not been completed.

IV. CONCLUSION

This paper presents a step-by-step methodology to develop a SOO for utility-operated microgrids. The method begins by determining the modes of operations applicable to the target microgrid and the envisioned transitions between these operating modes. Then, a high-level diagram of operating mode transitions is developed to provide a complete view of all potential transitions between grid-connected, load transfer, islanded, and clustering modes of operation. Finally, the SOO of the microgrid is laid out as an overall process flowchart where various sub-processes are developed to provide full details of control actions and switching commands to complete the SOO in each transition scenario.

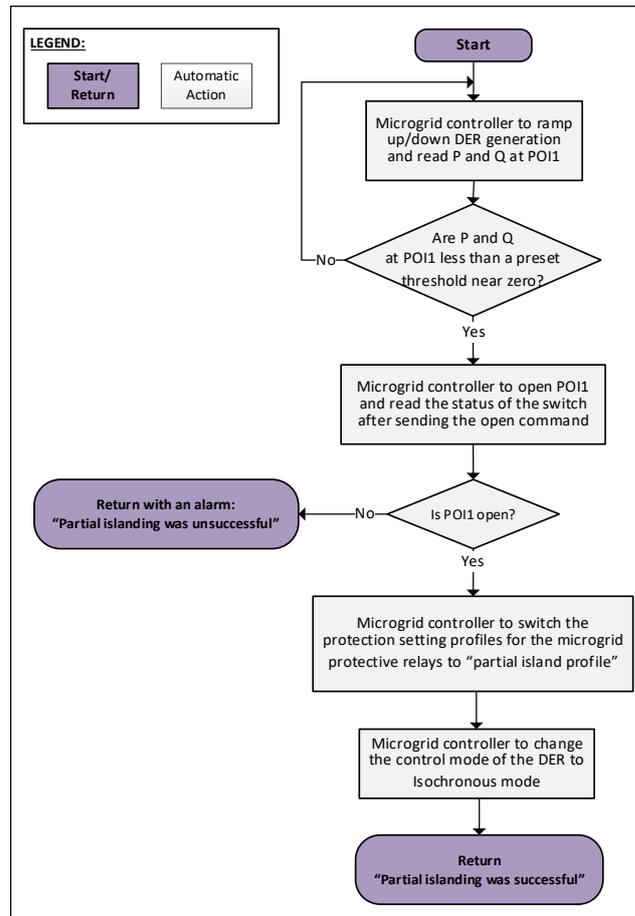


Fig. 4. The sub-process flowchart for planned partial islanding for the example microgrid configuration

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