Coordinated Failure Response and Recovery in a Decentralized Microgrid Architecture

Abedalsalam Bani-Ahmed, Mohammad Rashidi, and Adel Nasiri
Center for Sustainable Electrical Energy Systems
University of Wisconsin-Milwaukee
baniahm2@uwm.edu, mrashidi@uwm.edu, nasiri@uwm.edu

***Abstract*—The challenge of failure management emerges in decentralized architectures due to the distributed nature of the layered control process. Failures in microgrid system may occur at the microgrid level or any of the control layers. A failure detection and response mechanism is required to attain a reliable, fault-tolerant microgrid operation. This paper introduces a Failure Management Unit as an essential function of the microgrid Energy Management System. The proposed system is applied to a microgrid case study and shows a robust detection and recovery outcome during a system failure. The real-time experimental results were achieved using Hardware-In-the-Loop platform. Coordination between controllers during the recovery period requires low-bandwidth communications, which do not add any significant overhead to the communication infrastructure.**

***Keywords*— EMS; Decentralized Architecture; Failure Management; Microgrids; Smart Grid.**

I. INTRODUCTION

The microgrid concept is experiencing a fast growth as it can play an effective role in electrical energy systems offering higher reliability and cost effectiveness. The complexity of microgrids is influenced by many aspects, location and economics lying at the top of the list. The major items within the cost of microgrids are the distributed generation assets, automation, optimization, development, and installation. Microgrid controller constitute nearly 15% of the total microgrid budget [1]. As a single point of failure, the controller drives the microgrid reliability feature, dictating valuation of the microgrid based on the reliability as the main investment measure. Decentralization of microgrid controller has been proposed as a potential solution to the reliability feature as well as the computational requirements of the centralized MG controller [2].

Energy Management System (EMS) is a control software that manages the power output among Distributed Generation (DG) components supporting the loads, and providing an automated seamless transitions between different modes of operation. In centralized architecture, MG controller is required to be computationally powerful in order to process a high traffic of real-time data from all microgrid components and loads in a timely manner. This dictates a reliable bidirectional (preferably multipath) communication infrastructure [9]. The advantage of implementing EMS is a centralized controller is the low complexity of implementation. However, as the number of controlled components increases, requirements of communication network bandwidth and computational capacity become a major bottleneck. Decentralization of the energy management system is preferable when this bottleneck becomes a concern. In the decentralized architecture, local controls and monitoring is handled by local decentralized controllers. The controllers communicate with the other local controllers through the communication network. The local controllers have the intelligence to make operational decisions on their own, without receiving the control signals from a central controller in the centralized EMS.

A true decentralized microgrid control architecture suggests deploying multiple local controllers in order to achieve seamless transients during the operation and acts as if the system has one central controller as shown in Fig. 1. Resource sharing must be guaranteed, where every controller shares the status of its own DER with the peer controllers in real-time. This requires naming scheme that guarantees unique identification of each controller and its local DER. Each controller must have an updated map of the whole system, especially for the inputs to the microgrid control algorithm running in each controller. This is a key requirement to protect the integrity of the system, otherwise, inconsistent algorithm outputs and control commands may arise, which can lead to disturbance in the microgrid operation. Scalability is an advantage of this architecture, the microgrid to be scaled up or down in terms of the number of power components without affecting the operation or re-engineering the control algorithm. This advantage is reflected on the plug-and-play capability of the system. Scalability also outcomes a fault tolerant system, where it maintains availability and operates at the minimum level of reliability. This also include the recovery process in case of faults and possible redundancy that may boost the reliability of the microgrid.

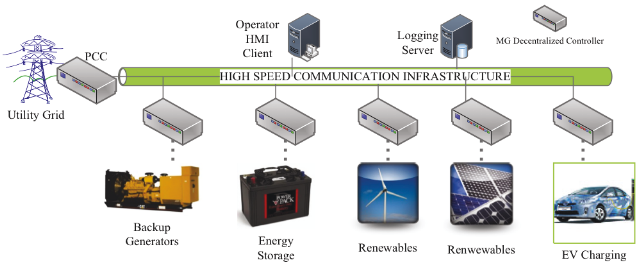


Figure 1. Microgrid Structure with Decentralized Communication Infrastructure.

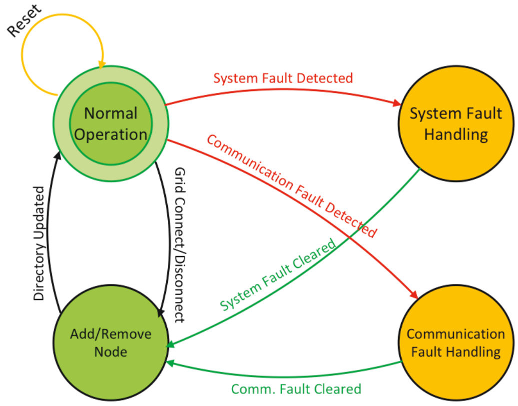


Figure 2. Controller state diagram with fault triggered state transitions.

In this paper, we propose a failure management system as an essential part of the microgrid EMS for decentralized microgrid control architectures. Detailed description of the proposed system is provided, tests are performed using Hardware-in-The-Loop (HIL) Platform developed for decentralized microgrid control architecture.

II. DECENTRALIZED MG ENERGY MANAGEMENT SYSTEM

In decentralized architectures, many challenges arise as the communication infrastructure between the controllers must be reliable without degrading the system reliability. Other challenges such as cyber-security concerns, this challenge is not entirely inherent in decentralized architectures, centralized architectures are considered vulnerable as long as the communications between the central controller and other components are present.

A. *Microgrid Failure Overview*

One challenge that needs to be addressed in any decentralized or distributed system is the system response to any component failure that may occur. To be considered a fault-tolerant system, each distributed component must have failure model that defines aspects that relate to system reliability and availability. Most importantly, designing a self-healing distributed control system relies mainly on the robustness of the recovery algorithm. Figure 2 illustrates controller state diagram with failure handling. Starting from normal operation, it is possible to reboot the controller at any time and return to the normal operation with no failures reported. If a fault is detected, the controller moves to system fault handling routine, the status flags reported by other controllers and runs the recovery algorithm; and the controller goes back to normal operation. Similar behavior is expected when detecting communication faults. Connections between peer controllers may fail due to network congestion or failure of the communication circuit, leading to faulty misinterpretation, and thus, inconsistent decision. If the distributed control system dedicated a local controller to the PCC, connecting or disconnecting to the grid requires adding or removing that controller from the directory based on the microgrid mode of operation.

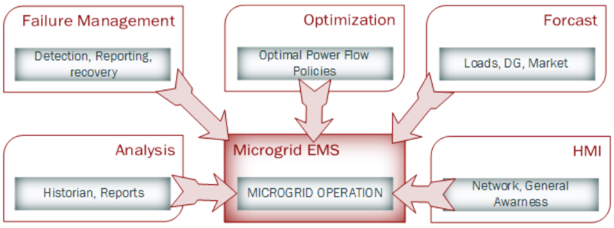


Figure 3 Illustration of Microgrid Energy Management System with Failure Management Unit.

B. *Failure Management Unit*

The Microgrid energy management systems ensures the is responsible for taking actions to minimize frequency and voltage deviations and restore the microgrid to desired set-points of operation. It usually involves a framework consisting of a communication system and an intelligent controller which can find an optimize unit commitment and dispatch the available energy resources. As shown in Fig. 3, the Microgrid EMS functional requirements involve forecasting [9], optimization [10], analysis, and Human Machine Interface (HMI) [11].

In decentralized architectures, the EMS is distributed over a pool of controls units and dispense of one control unit. The need to manage the failure of these controllers arises. Failing hardware or software will disturb the overall operation of the microgrid, as the sensitivity of the microgrid bus is high due to the lack of inertia [10]. The main function of the FMU is to perform a system recovery process when a system failure occurs, to maintain the microgrid operational during the recovery. Figure 4 shows the structure of the proposed FMU, inputs of failure detection sources explained in the following section is received locally, failure detection is performed, and the recovery routine is processed to provide the local DER with power flow command (if any). The unit generates a report which is attached to the status updates to the peer controllers.

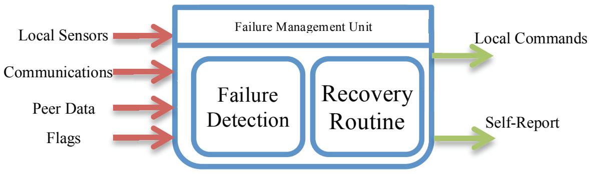


Figure 4 Proposed structure of the Failure Management Unit.

III. FAILURE DETECTION METHODS

The failure detection unit described in the previous section receives the data from the control environment and runs a failure detection algorithm. The proposed system adopts the following failure detection methods:

A. *Local Sensing*

Sensing local microgrid parameters is essential for microgrid operation control. Leveraging the data collected via local sensing, disturbances can be analyzed in order to predict any possible failures in the system. Voltage or frequency changes interpreted as a failure in one power component. Assume a microgrid with n distributed controllers; for a controller C_i at time t, local voltage and frequency sensing is governed by (1) and (2), respectively.

$$V_{Bus}|_t = e_V V_{C_i} = 1\, p.u \qquad i = 1,2,\dots,n \qquad (1)$$
$$F_{Bus}|_t = e_F F_{C_i} = 60\ Hz \qquad i = 1,2,\dots,n \qquad (2)$$

Where e_x is the allowed mismatch factor to remain in normal operation state.

B. Communications

Decentralized architecture dictates the presence of a reliable communication network connecting all peer controllers. Various communication protocols can be applied to such system. Decentralized controllers are designed to have some level of intelligence, Delays and timestamping mismatch can be interpreted as a failure of a controller, which triggers the rest of the system to react accordingly. In TCP/IP [4], the lack of acknowledgment for the 3-way handshake with any peer controller can be interpreted as a failure, and must be reported.

C. Peer Reports

We propose a technique for failure detection based on reporting from peer controllers. Since all controllers sends their own status updates and local measurements, a peer report segment (Fig. 5) is allocated in order to broadcast any detected failures. Some controllers may detect failures before others, or a failing communication link between two controllers which could not be detected by local sensing or communications techniques. This technique speeds up the system fault handling as all controllers are informed about any occurring failures.

D. Self Reports

Self-reporting technique is initiated in the controller locally, and broadcasted within the status update. The local controller performs a sanity check, detecting or predicting any failure that may occur at any time. This allows the decentralized controllers to respond faster in case the failure occurs and the system heals in a faster manner that depending on local sensing or communications techniques.

IV. COORDINATED FAILURE MANAGEMENT

Assume a microgrid where a decentralized control architecture is applied (Table 1). The utility grid is assumed to be a power component when the microgrid is in grid-connected mode. At any time t, the output power is bounded by the following constraints

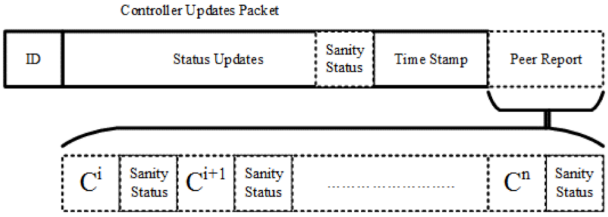
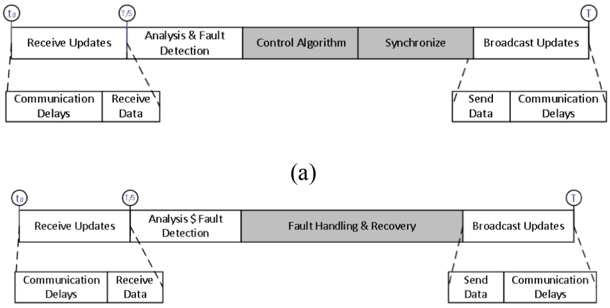


Figure 5 Status update packet with allocated peer report.



(a)

(b)

Figure 6. (a) Control Cycle during normal operation. (b) Control Cycle during state transitions.

$$P_{NG}^{min} < P_{NG}(t) < P_{NG}^{rated} \qquad (3)$$

$$0 < P_W(t) < P_W^{rated}(t) \qquad (4)$$

$$0 < P_{PV}(t) < P_{PV}^{rated}(t) \qquad (5)$$

$$\left.\begin{array}{c} P_{ES}^{min} < P_{ES}(t) < P_{ES}^{rated} \\ E_{ES}^{+} = E_{ES}(t) + P_{ES}(t)\,\Delta t \\ E_{ES}^{+} > E_{ES}^{min} \end{array}\right\} \qquad (6)$$

Where $P_x(t)$ is the power output of source x at time t. P_x^{rated} is the rated power of the source. For Energy Storage (ES), E_{ES}^{+} is the available energy in storage projected after Δt, E_{ES}^{min} is the minimum energy storage allowed in ES, which reflects the minimum state of charge (SOC).

TABLE I. MICROGRID CASE STUDY COMPONENTS

Power Component	Rated Power	Dispatchable
Natural Gas Generator	P_{NG1}^{rated}	Y
Natural Gas Generator	P_{NG2}^{rated}	Y
Energy Storage	P_{ES}^{rated}	Y
Wind Turbine	P_{W}^{rated}	N
Solar Panels	P_{PV}^{rated}	N
Utility Grid	P_{PCC}^{rated}	Y

A. Control Cycle Operation

The system is considered in normal operation when the following conditions are met: 1) Equations (1) and (2) are not violated, where the bus voltage and frequency are within limits. 2) Sanity check performed locally results a valid condition. 3) Peer reports are all valid stating that all controllers are working properly and the system is stable. Figure 6 shows the control cycle of any decentralized controller, the failure analysis is performed right after the updates are received from all peers. In the case of no violations have been detected, nor any failure have been reported, the control algorithm maintains at normal operation. If the output from failure analysis and detection is a failure code, the fault handling and recovery takes over and the normal operation algorithm halts.

B. Failure Response and Recovery

In order to manage the power supply among all sources, unit commitment algorithm is necessary. Unlike other EMS

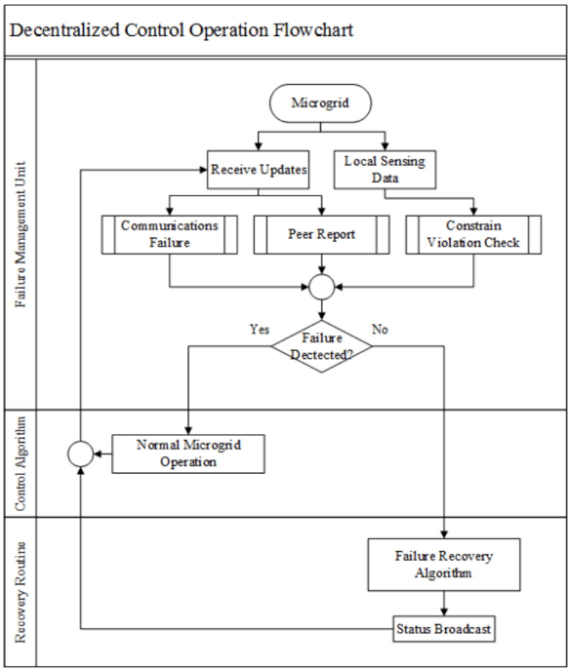


Figure 7 Failure detection and response algorithm.

operations, failure management becomes an essential component of the unit commitment algorithm or the economic dispatch function when decentralized control architecture is deployed. At any time t, active and reactive power output of sources and the consumption of loads follows equations (7) and (8).

$$P_{net}|_t = \sum_{i=1}^{n} \left(e_P P_{C_i}\right) = 0\, p.u \tag{7}$$

$$Q_{net}|_t = \sum_{i=1}^{n} \left(e_Q Q_{C_i}\right) = 0\, p.u \tag{8}$$

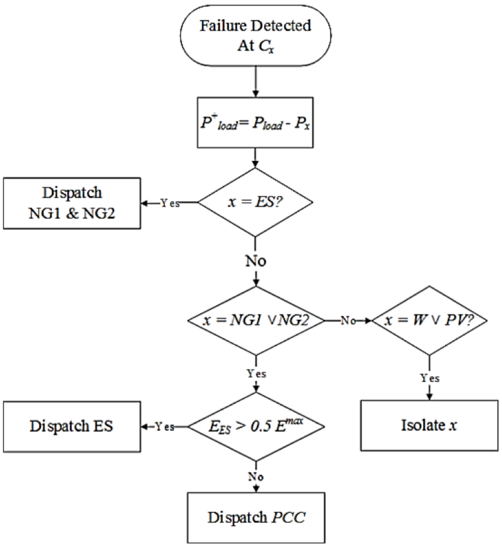


Figure 8 Failure Recovery Algorithm.

Where P_{net}, Q_{net} are the net active and reactive power respectively between generation and consumption at any given time t. e_P, e_Q are the allowed mismatch factors to remain in normal operation state for active and reactive power, respectively. Figure 7 shows a flowchart describing the overall operation for failure response and recovery for the microgrid in Table (1) and unit commitment including controller failure recovery. The main purpose of the algorithm flowchart in Fig. 8 is to maintain two objectives in islanded mode: 1) At least one power source with voltage and frequency control capability in order to maintain the voltage and frequency of the bus. 2) Meet the power demand by the loads. The output from the failure management unit (Fig. 7) provides the failure signal and the location of that failure, which becomes an input to the algorithm in Fig. 8.

V. RESULTS

In order to test the robustness of the failure management unit, a comparison to a scenario of normal microgrid operation is performed. The microgrid operates in island mode, energy storage regulates the voltage and frequency of the bus during the transition period. Figure 9 shows the active power curves captured over 130 seconds period. The system simulation starts with fully charge ES. NG1, NG2 are off and their breakers are open. The nature of the loads varies with time starting with 60 KW and increasing. ES provides the power to the loads for 16 seconds until the decentralized controller at the ES unit detects 60% SOC on remaining on the battery. As a decentralized system and with general awareness condition is maintained; DMGC of NG1 sends a command to NG1 to start and synchronize with the bus, and commands the breaker after 6 seconds providing 190KW (full capacity). Since the load demand is greater than the capacity of NG1, DMGC of NG2 detects the issue and connects at t = 26s. The DMGC if ES detects that NG1 and NG2 are active, and moves to charging mode.

Figure 10 illustrates the case for failure of one decentralized controller, the chosen controller for this case is the NG1, which could be one of the extremist cases since the generator could be regulating the bus voltage/frequency. At t=47.5s, the controller of NG1 fails while both generators are running and the ES is in charge mode. Two controllers can respond to this change based on Fig. 8, ES controller can command ES to take over, or the PCC controller can command emergency grid connection. For this case, PCC responds since the SOC of the battery is critically low, and NG1and NG2 are shut down. One other case where microgrid may not support non-intentional grid connection, load shedding must be performed and NG2 may remain running until the failure clears. In order to prove the scalability of a decentralized control architecture, NG1 controller returns to the system at t=66s and the reconnection operation is performed. The return of NG1 is reported to the rest of the controllers in order to return to normal operation mode.

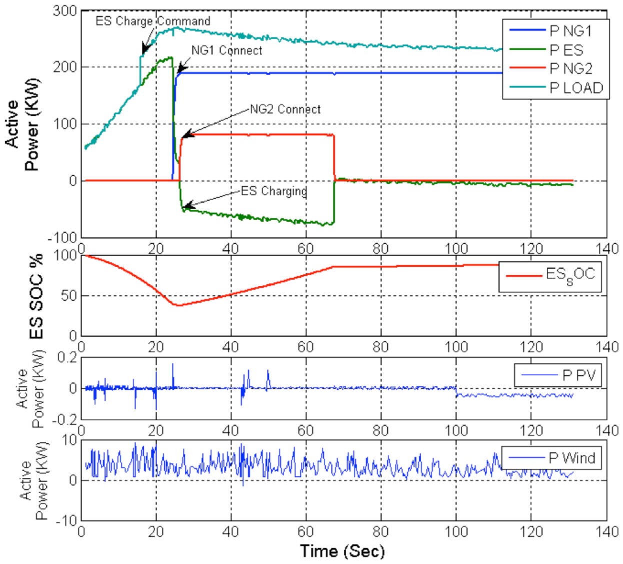


Figure 9 Normal Operation of Decentralized Microgrid Control Architecture.

VI. CONCLUSIONS

Failure management becomes a challenge when a central management system is distributed over a layer of controller. This paper introduces a failure management unit as an improvement of microgrid energy management system. The proposed unit handles failure detection and recovery process, and guarantees a seamless transient response after the fault. Experimental results shows the robustness of the proposed system when applied to decentralized control architecture for micrograms. Adopting four methods of failure detection speeds up the recovery process, as they guarantee a fast propagation of system updates among the controllers. Future work of this effort may include additional intelligence to the controller. Prediction techniques can be adopted in order to provide a near future prediction of a failure, and speeding up the recovery process. This requires a historian buffer which carries a history data for the overall microgrid system.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. 1650470. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

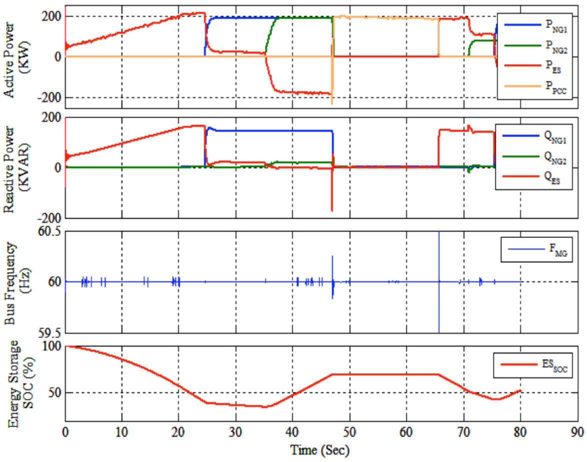


Figure 10 System response to failure in one decentralized controller on microgrid operation.

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