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Reliability Analysis of a Decentralized Microgrid Control Architecture

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***Abstract*— Reliability enhancement of microgrids is challenged by environmental and operational failures. Centrally controlled microgrids are susceptible to failures at high probability due to a single-point-of-failure, e.g. the central controller. True decentralization of microgrid architecture entails elimination of the central controller, attaining a parallel configuration for the system. In this paper, decentralized microgrid control architecture is proposed as a solution for reliability degradation over the time, and analyzes the reliability aspects of centralized and decentralized control architectures for microgrids. Degree of importance of a single controller in centralized and decentralized architectures is determined and validated by Markov Chain Models (MCM). Results confirm that higher reliability is achieved when true decentralization of control architecture is adopted. Challenges of implementing a true decentralized control architecture are discussed. Hardware-In-the-Loop simulation results for microgrid controller failure scenarios for both architectures are presented and discussed.**

Index Terms—Decentralized control, distributed control, HIL, Markov Chain, microgrid, reliability, smart grid.

I. Introduction

The usage of the terms smart grid and microgrid are growing immensely, feeding from the multi-disciplinary pool of research and visions for the electrical grid. The basic concept of Smart Grid is to add monitoring and communication to existing partially traditional grid [1]. It also adds control in a manner that moves this traditional grid into a two-way power and information flow entity. This will allow new forms of generations and energy storage to connect to the system and participate in many mainstream and ancillary functions of the grid.

Acting as one of the drives of Smart Grid advancement, microgrids are a localized grouping of electricity sources and loads that normally operate connected to and synchronous with the traditional centralized grid (macrogrid), but can disconnect and function autonomously as physical and/or economic conditions dictate [2]. Figure 1 shows a generic illustration of the microgrid concept within the electric power grid map. The distribution network in the power grid supports residential and industrial areas providing utility services where microgrids are deployed in order to support local power demand and respond to ancillary services requests.

Typical microgrid requirements involve grid connection capabilities, and optimization of economic operation, and support integration of high penetration and energy harvesting

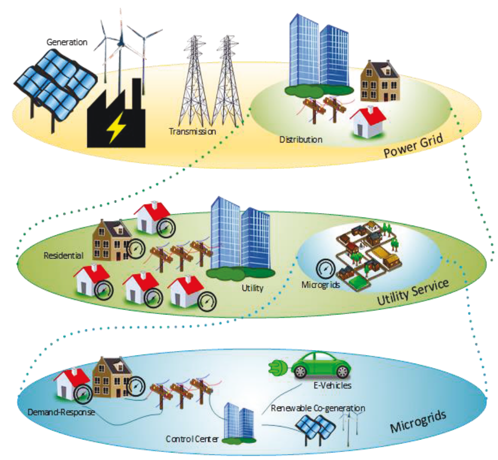

Figure 1. Residential Microgrid location on the power grid map.

for renewables. Microgrids also support market participation of smaller power sources that can be aggregated to provide power necessary to meet the target goals for Distributed Energy Resources (DER) [9]. As the electricity grid continues to modernize, DER such as storage and advanced renewable technologies can help facilitate the transition to a smarter grid islanding capabilities. Microgrids also support management of critical and non-critical loads for available generation. Other microgrid requirements involve secure operations, deploying cyber secure communications network that guarantee distributed and resilient supervisory control architecture.

Studying microgrid reliability is a challenge due to the variety of power sources that can be included [22]. Generally, the evaluation of microgrid reliability must consider the load demand, which influences the microgrid architecture at the design stage [2]. Other aspects such as protection schemes are considered as a microgrid reliability enhancement mechanism [3] [4]. The advancement of power electronics research efforts and control strategies for microgrid inverters, and hybrid AC-DC microgrids had invigorated power systems researchers in general to adopt state of the art technologies in designing reliable microgrid systems [5]. Communication-assisted control techniques drove the improvement of microgrid reliability arising cyber-security concerns [13].

The focus of this paper is microgrid reliability enhancement and analysis by decentralizing the control architecture. Although the scope of the paper does not involve a specific control mechanism, section II reviews state of the art microgrid control strategies including decentralized controls. Microgrid reliability analyses are discussed and conducted

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providing a quantitative evidence of the reliability improvement in decentralized microgrids as opposed to the centrally controlled microgrids in Section III. Section VI discusses experimental results of a microgrid during normal operations and the impact of controller failure in centralized and decentralized control concepts.

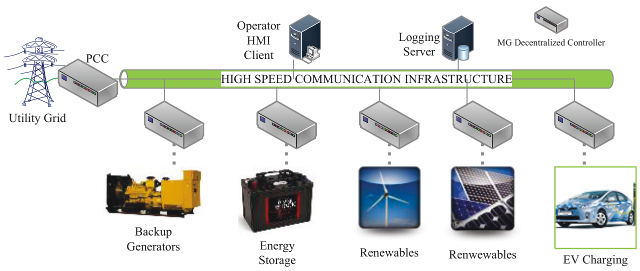

Figure 2. Decentralized Microgrid control system architecture with communication infrastructure.

II. Microgrid Control Strategies

Control strategies for microgrids have been developed for the past decade targeting the seamless transients and microgrid operations. Control of microgrids is generally more complex than traditional power systems due to limited energy storage capacity and lack of inertia, fast dynamics and short response time of inverter-based distributed resources, and a high degree of parametric and topological uncertainties [11]. These issues transform into more complex challenges when the system reliability is at risk, and a robust control architecture becomes essential as smart grid functionality is enabled [1]. That includes the intelligent interconnection and integration of DERs, demand response, and consequently achieving net metering.

Control methods can be categorized based on the control architecture design, communication infrastructure, load sharing strategy. Centralized and distributed (decentralized) control methods differ in many aspects, the major aspect involves data concentration power sharing command sources. Generally, if the DGs are capable of generating commands locally, regardless of the presence of communication with other DGs, this is considered to be a distributed control.

Centralized microgrid control consists of the central controller that monitors and controls all DER units and local loads [16]. Decentralized microgrid control is virtually centralized, that is, the central controller is physically distributed over a decentralized infrastructure. As shown in Fig. 2, the architecture suggests deploying multiple local controllers to achieve seamless transients during the operation control scheme. Resource sharing must be guaranteed, where every controller shares the status of its own DER with peer controllers in real-time manner. This requires a naming scheme that guarantees unique identification of each controller and its local DER. Each controller must have a general awareness of the whole system status, 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 disturbances in microgrid operation [18]. The decentralized control is a variant on the master/ slave control. A local decentralized controller controls the reference voltage and influences the output current of the units. The voltage magnitude, frequency and power sharing are locally controlled. Hence, in decentralized control, only low bandwidth communication is required to exchange local updates with the peer controllers [12].

Microgrid control hierarchy as illustrated in Fig. 3, has three levels of controls where each level satisfies certain requirements and roles maintaining power reliability, quality, and economical concerns [12]. Primary control level comprises two control loops for voltage and current, playing an essential role in stabilizing the voltage and frequency. The voltage/angle or active/reactive power commands are provided from the secondary control and voltage and current references are generated and provided to the source.

Although the primary control level is responsible of frequency regulation, some deviation may occur due to the load power demand fluctuations or intermittency of renewables. In microgrid systems, energy storage enables the microgrid to compensate for frequency deviations for short terms, the role of secondary control comes at a slower response to frequency fluctuations in comparison the primary control ensuring power quality. The control system continuously monitors the microgrid frequency and voltage in real time, and dispatches microgrid components such as energy storage or backup generators for active and reactive power and updates the primary levels at each power source with the appropriate power command [15].

Local frequency control [13] and voltage regulation [14] at the primary control level are the major drives for decentralized controls of microgrids. Other controlled variables including active and reactive power are managed by the Energy Management System (EMS) at the secondary and tertiary control levels [15]. The variation of decentralized primary control techniques for different microgrid components as grid-forming and grid-feeding sources relies on the behavior of the component and the controllability of microgrid variable at the source terminal. As microgrid topologies varies, the control methods consider inverter-based power sources [17] only, or a

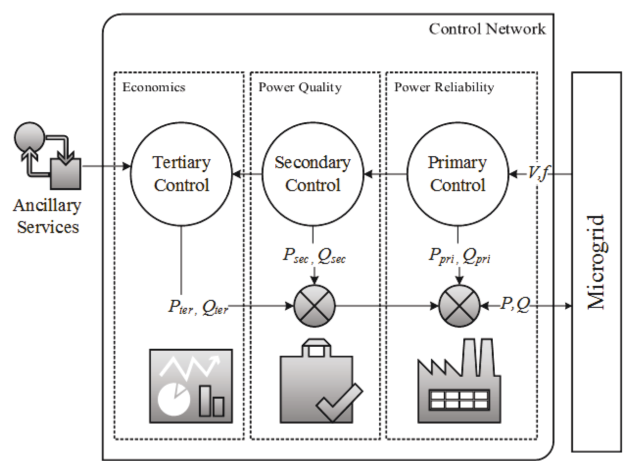

Figure 3. A typical microgrid control hierarchy.

combination of AC and DC sources [9] [18]. Methods have

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been proposed enabling real-time management of microgrids involving energy storage units over a decentralized secondary control architecture [12], [16]. In this paper, the architecture under investigation applies the Virtual Droop Control method [21].

A decentralized secondary level coordination is essential when parallelization of DERs in microgrids is achieved and the purpose of parallelization is maintained. Feedback to the control loop can be local measurements of the power source, or status updates from other components over the communication infrastructure as shown in Fig. 2, or both. Although the system is connected at the network level, the scalability is possible when we overcome the challenge of dynamic configuration of the control algorithm, and true decentralization is applied to the control architecture. The tertiary control level manages the bidirectional power flow between the microgrid and the grid at the point of common coupling (PCC). This level also ensures optimal economical operation of the microgrid (Fig. 3).

Scalability is an advantage of decentralized architecture, when the microgrid grows in terms of the number of power components without disrupting the operation or re-engineering the control algorithm. This advantage influences 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 demands a recovery algorithm as a part of the energy management system and certain level of redundancy to boost the reliability of the microgrid system.

III. Microgrid Control Reliability Analysis

Microgrids can be deployed for various purposes in an island or grid-connected structure. For example, a microgrid intended to operate in two modes (grid-connected and islanded) can be dispatchable, serving the purpose of supporting the distribution system. Distant microgrids away from the grid usually serve the purpose of continuously and independently supporting local loads. Loads can be categorized into critical and non-critical, and their characteristics can vary from static to dynamic behaviors. Regardless of the type, microgrids under any disturbance or fault condition have different behavior and performance, while supporting critical loads. The reliability analysis of microgrids is performed here based on three objectives: (i) Supporting critical loads, with the assumption of partially shedable loads, (ii) Microgrid bus voltage regulation, and (iii) Microgrid bus frequency regulation.

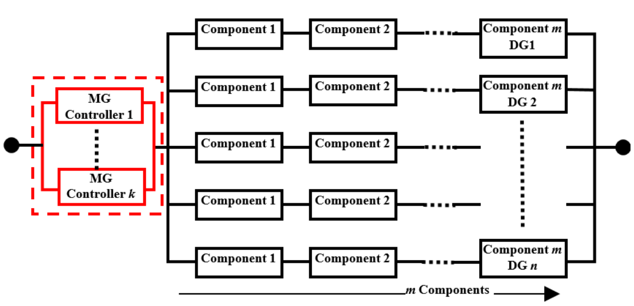

Figure 4. Reliability block diagram of a microgrid architecture.

A. Reliability Measurements

1) Degree of Importance

The importance of a component indicates the impact of the component's failure on the system failure [19]. In the early stages of system development, the components life distribution or reliabilities are assumed to be equal.

A system with n components, considering a state x_i of component i is defined by:

$$x_i = \begin{cases} 1 & \text{if } i \text{ is functioning} \\ 0 & \text{if } i \text{ is } \textbf{not} \text{ functioning} \end{cases} \quad i \in (1, n) \tag{1}$$

A deterministic binary function φ of the system state, with x as the function vector input $x = (x_1, x_2, \ldots, x_n)$ is defined as follows:

$$\varphi(x) = \begin{cases} 1 & \text{if the system is functioning} \\ 0 & \text{if the system is not functioning} \end{cases} \tag{2}$$

In our case, it is possible to calculate the structural importance of a component i in structure φ using [19] (3).

$$I_\varphi(i) = \int_0^1 (h(1_i, P) - h(0_i, P))dp \tag{3}$$

Where $h(1_i, P)$ is the probability that the system operates with no failures, and $h(0_i, P)$ is the probability that the system fails when component i fails. As defined in the function of component reliabilities

$$(1_i, P) = (x_1, \ldots x_{i-1}, 1, \ldots, x_n) \tag{4}$$

$$(0_i, P) = (x_1, \ldots x_{i-1}, 0, \ldots, x_n) \tag{5}$$

Figure 4 shows the reliability block diagram of a possible microgrid configuration. Each block represents one possible component or a subsystem with a pre-defined failure rate. A working system remains while a continuous line from left to right is maintained.

Higher reliability of a system is proportional to the degree of parallelization of the reliability model [22]. In microgrids, the controller is a vital component to maintaining operation. As shown in Fig. 4, The red portion of the diagram represents a controller as in series block to the system. Failure of the controller breaks the line and the system is declared in failure state.

Decentralization of the control architecture transforms the series-parallel reliability block diagram in Fig. 4 into a parallel system [22], which decreases the degree of importance of a controller in the architecture. The degree of importance of a controller is calculated using (3) for three cases: 1) Centralized controller architecture. 2) Redundant control architecture with two controllers. 3) True decentralized control architecture.

Equations that govern the importance of three cases from equations (3-5) are

Case 1) Centralized:

$$\left.\begin{aligned} R_{Cen}(t) &= R_{CMGC}(t) * R_{PS}(t) \\ R_{Cen}(t) &= P_{con}(1 - (1 - P_{com}^{m})^{n}) \\ h(1_{Ccon}, P) &= 1 - (1 - P^4)^5 \\ h(0_{con}, P) &= 0 \end{aligned}\right\} \tag{6}$$

Case 2) Redundant:

$$\left.\begin{aligned} R_{RED}(t) &= R_{RMGC}(t) * R_{PS}(t) \\ R_{RED}(t) &= 1 - \left(1 - P_{con}\right)^2 * (1 - (1 - P_{com}^{m})^{n}) \\ h(1_{Rcon}, P) &= 1 - (1 - P_{com}^4)^5 \\ h(0_{Rcon}, P) &= (1 - \left(1 - P_{con}\right)) * 1 - (1 - P_{com}^4)^5 \end{aligned}\right\} \tag{7}$$

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Case 3) Decentralized:

$$\left.\begin{array}{c} R_{DEC}(t) = R_{PS}(t) \\ R_{DEC}(t) = (1-(1-P_{com}^{m})^{n}) \\ h(1_{Dcon}, P) = 1-((1-P_{com}^{4})^{4} * (1-P_{com}^{3})) \\ h(0_{Dcon}, P) = 1-(1-P_{com}^{4})^{4} \end{array}\right\} \quad (8)$$

Where $R_{Cen}(t), R_{Rcon}(t), R_{Dcon}(t)$ are the total system reliability for the three cases, respectively. $R_{CMGC}(t), R_{RMGC}(t), R_{DMGC}(t)$ are the controller reliability for each case. $R_{PS}(t)$ is the reliability of the system not including the controller (parallel section). P_{con} , P_{com} are the failure probabilities of a controller and any other component, respectively.

Figure 5 shows the calculation results of importance calculations in a microgrid control architecture for the three cases. Assuming four components in a parallel branch, and varying the number of possible DGs in a microgrid. Scaling up the microgrid, the importance of a controller increases in the centralized architecture even with a redundant controller. However, due to parallelization in decentralized architecture, the importance of each controller decreases as the microgrid expands in numbers.

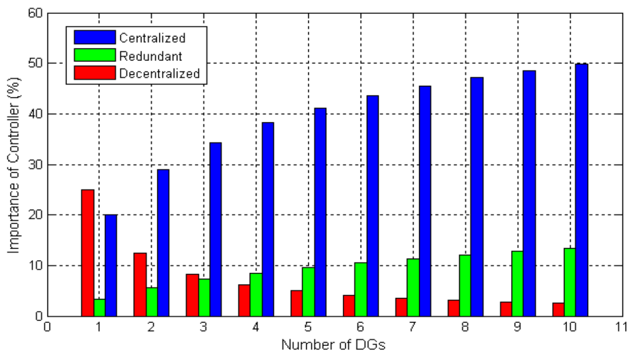

Figure 5. Controller Degree of Importance in three Centralized, Redundant, and Decentralized Architectures.

2) Markov Chain Analysis

Markov Chain Reliability Model (MRM) uses a stochastic process which may describe complex behavior of a stochastic system. MRM is being used to model a system with several states and transitions between states. A Markov reliability model contains a series of the possible states in the system and uses possible failure rates and repair rates between those states. One of the advantages of using Markov Chain Modeling is the capability of computing the steady state probabilities of all system states, and estimating probability of rarely occurring events and failures. The practical values of failure rates used in our simulations can be found in [20].

Markov Chain modeling works with systems that are relatively small in terms of number of states. Larger systems (i.e power systems) can have thousands of states, and requires additional techniques in order to achieve faster computation without losing the accuracy of the model.

Given *X(t)* a random variable in Markov process, the transition probability function between two states *i, j* is denoted as

$$P_{ij}(\Delta t) = P[X(t+\Delta t) = j \,|X(t) = i] \quad (9)$$

The transition from state i to j depends on the transition time interval Δt, and does not have a memory characteristic. For a system of n states, a probability transition matrix is defined as

$$\boldsymbol{P}(\Delta t) = \begin{bmatrix} P_{11}(\Delta t) & P_{12}(\Delta t) & \dots & P_{1n}(\Delta t) \\ P_{21}(\Delta t) & P_{22}(\Delta t) & \dots & P_{2n}(\Delta t) \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1}(\Delta t) & P_{n2}(\Delta t) & \cdots & P_{nn}(\Delta t) \end{bmatrix} \quad (10)$$

Where

$$P_{ij}(\Delta t) \geq 0 \quad i,j \in [1,n] \quad (11)$$

$$\sum_{j=1}^{n} P_{ij}(\Delta t) = 1, \;\; i \in [1,n] \quad (12)$$

Equation (10) can be written as (13) due to homogeneous property.

$$P = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ P_{21} & P_{22} & \dots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{nn} \end{bmatrix} \quad (13)$$

Markov reliability models can be simulated based on failure rates λ of system components instead of probability of failure P, forming a transition matrix *M*. If the system is repairable, repair rates μ are included to the transition matrix [20]. Simulation of the reliability model results with a predicted reliability of the system. An example of such technique is proposed in the next section.

B. Reliably of Decentralized Control Architectures

Figure 7 shows the proposed microgrid decentralized control architecture. By eliminating the centralized controller of a conventional architectures, the system transforms into certain number of parallel branches (subsystems). For this study purposes, each branch is assumed to have four components: the local decentralized controller, and two communication lines and the distributed generation (DG) unit. As an example, the DG in the expanded branch illustrates a PV system.

A review of literature was performed to identify the failure rates for each component. The reliability of a controller is governed by the quality of the material and the possible protection mechanisms. Software wise, the decentralized algorithm is more complex and more susceptible to logic errors if the software engineering level was not adequate. Due to the various factors, the possibility of establishing a firm comparison between centralized and decentralized controllers' failure rates was irrelevant, So, we followed the literature by using the equal failure rates for the corresponding components

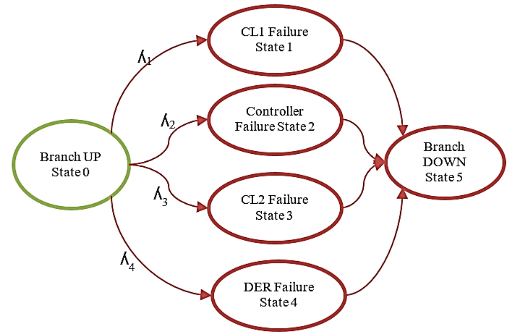

Figure 6. Markov model and state transition diagram for a parallel branch.

of both architecture..

Markov reliability model for the system in Fig. 7 results with transition matrix representing 241 states, for *n=5* DGs in centralized architecture, and 2^{40} in decentralized architecture. Due to large number of states. Lumping technique is used to simplify the transition matrix for the Microgrid System [20]. Reliability of each branch is evaluated using Markov modeling. Two cases are considered, repairable and non-repairable. In a non-repairable system, failure of any component is considered permanent. A repairable system is a practical case in power systems, where a failed component is repaired or replaced after failure is discovered. Markov chain simulation predicts the steady state reliability of the system. A repairable system converges to certain reliability with time, on the contrary of a non-repairable system where the reliability curves converges to zero, depending on the length of the simulation interval intended for analysis.

Table 1 BRANCH STATES AND THEIR CORRESPONDING RELIABILITY EQUATIONS.

State	DER $R_1(t)$	CL2 $R_2(t)$	LC $R_3(t)$	CL1 $R_4(t)$	System State C	*P(t)*
0	Up	Up	Up	Up	Up	$R_1(t).\ R_2(t).\ R_3(t).\ R_4(t)$
1	Down	Up	Up	Up	Down	$(1-R_1(t)).\ R_2(t).\ R_3(t).\ R_4(t)$
2	Up	Down	Up	Up	Down	$R_1(t).\ (1-R_2(t)).\ R_3(t).R_4(t)$
3	Up	Up	Down	Up	Down	$R_1(t).\ R_2(t).(1-R_3(t)).\ R_4(t)$
4	Up	Up	Up	Down	Down	$R_1(t).\ R_2(t).\ R_3(t).(1-R_4(t))$

Table 1 represents a branch states of Fig (6). The total reliability of the branch *P(t)* depends on the previous state. The reliability equation for each state follows the reliability equations in [22]. For each branch, the transition matrices as non-repairable and repairable cases as shown in Fig. 6 are depicted in equations (14) and (15), respectively. For a branch that comprises of 4 components in series, any component failure will cause a failure in the whole branch due to the high dependency of the component to each other. The branch moves from an UP state to an intermediate state at different failure probabilities (rates), which represents a DOWN state of the whole branch. Each branch will be considered a subsystem of a microgrid, with a failure rate determined using equation (14) or (15), depending on the reparability of each component.

$$M_{No\_Repair} = \begin{bmatrix} * & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{14}$$

$$M_{Repair} = \begin{bmatrix} * & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 \\ \mu_1 & -\mu_1 & 0 & 0 & 0 \\ \mu_2 & 0 & -\mu_2 & 0 & 0 \\ \mu_3 & 0 & 0 & -\mu_3 & 0 \\ \mu_4 & 0 & 0 & 0 & -\mu_4 \end{bmatrix} \tag{15}$$

The asterisk value is the negative summation of the rest of the row. Similarly, given a microgrid with 5 DGs, transition matrices are implemented. Using lumping technique, the number of states are reduced, since the microgrid are now consisting of 5 subsystems in addition to the controller (in case of centralized). Equations (16) and (17) shows the transition matrices for both cases.

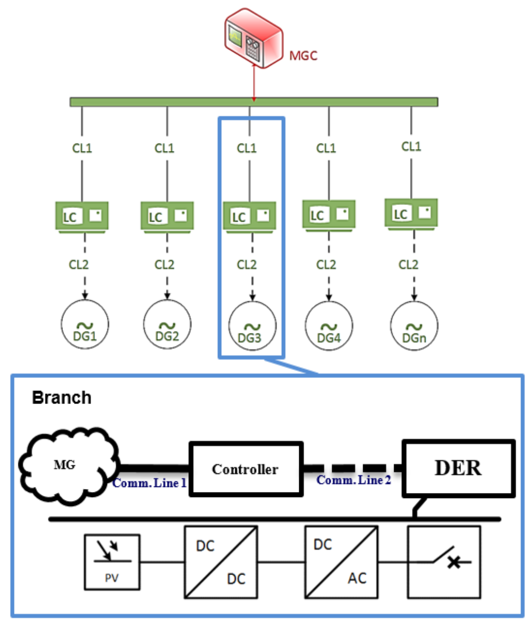

Figure 7. Microgrid Decentralized Control Architecture (Green). Eliminated centralized controller (Red). Example branch components (Subsystem).

$$M_{Centralized} = \begin{bmatrix} A \\ B \\ C \\ D \end{bmatrix} \tag{16}$$

Where *A* and *B* are 20X64 matrices. *A* and *B* represent the acceptable states and critically acceptable states respectively (total of 20 states). At these states, the centralized controller is in working state, while in *C* and *D* (44X64 matrices)*,* the controller is down and the microgrid system is considered down or unstable and requires shutting down (total 44 states). In case of decentralization of controls, the transition matrix is reduced to 50% in terms of number of states since a single point of failure has been eliminated which is depicted as the red portion of the block diagram in Fig.4. The transition matrix for this case is defined as

$$M_{Decentralized} = \begin{bmatrix} A \\ B \end{bmatrix} \tag{17}$$

Where *A* and B are 20x32 and 12x32 matrices, respectively. The failure states follow the same description of the centralized transition matrix.

Markov Chain simulation is conducted using MATLAB©. equivalent failure rates for each branch is calculated for the equivalent fault tree according to the rates in [20]. The main purpose of such analysis is to identify the improvement of the overall microgrid system reliability moving from centralized to decentralized architecture. Another purpose is to study the impact of a single controller on the overall system in both architectures. The probability distribution vector (18) is obtained using the transition matrix.

$$P(t) = [P_0(t) \dots P_n(t)] \tag{18}$$

$$\dot{P}(t) = P(t) \cdot M \tag{19}$$

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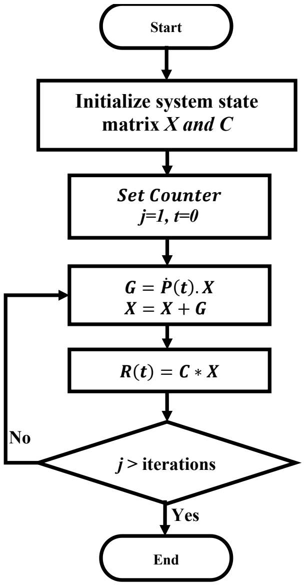

Figure 10 Markov Chain Simulation flowchart

Where X is the initial state of the system $X = [1, 0, \ldots., 0_{n-1}]$, *n=32 or 64* (decentralized, centralized). C represents the states where the microgrid system is in a healthy state $C = [1, 1, \ldots., 0, 1, C_{n-1}]$. Initially, the iteration counter is set to *j=0*, and the simulation loops until the number of iterations is reached. The number of iteration is determined using the following equation:

$$Iterations = \frac{Total\ simulation\ time}{\Delta t} \quad (20)$$

The results of the Markov reliability simulations are illustrated in Figures 9-10. Figure 9 shows the reliability curves of the overall microgrid system for the two architectures: centralized and decentralized. The reliability function *R(t)* is the probability that an item does not fail in the time interval (0, t]. In centralized case, the overall microgrid reliability decreases with time and goes below 50% at 2.5 years, in comparison to approximately 90% with decentralized architecture. However, for a practical case where the system is repairable; the reliability of the microgrid converges to 56% in 12 years with a centralized architecture compared to a 94% for the same time period in decentralized architecture.

Four improvements of controller failure rates are included in simulations results in Figures 8 and 9, reflecting 20% decrease in failure rate of single controller. The failure rate is reapplied to the transaction matrix *M* for each improvement. The failure rate is calculated using the following equation

$$\lambda_c^{q+1} = 0.8\lambda_c^q \quad (20)$$

Where λ_c^{q+1} is the new failure rate of the controller, and λ_c^q is the previous failure rate.

Validating the results in Fig. 5, the degree of importance of a single controller on the overall system reliability is larger in the case of centralized architecture. Generally, scaling up the microgrid (increasing the number of DGs), the overall reliability of the microgrid is improved when the architecture is decentralized, unlike the centralized architecture where the reliability decreases.

IV. Experimental Results

A. Decentralized Architecture Implementation

For testing purposes, a Hardware-In-the-Loop (HIL) platform [12] were developed to study microgrid operations with real physical communication layer and applying the decentralized architecture shown in Fig. 7. A dedicated workstation running microgrid simulation model. The workstation is equipped with multi-Ethernet ports, binding the model with a dedicated Ethernet port serves the purpose of avoiding impractical network congestion with other network related traffic, i.e. Internet. PSCAD is an ideal candidate for our platform. The simulator is widely used for multi-phase power systems and control networks in time domain, and mainly dedicated to the study of transients of power system,

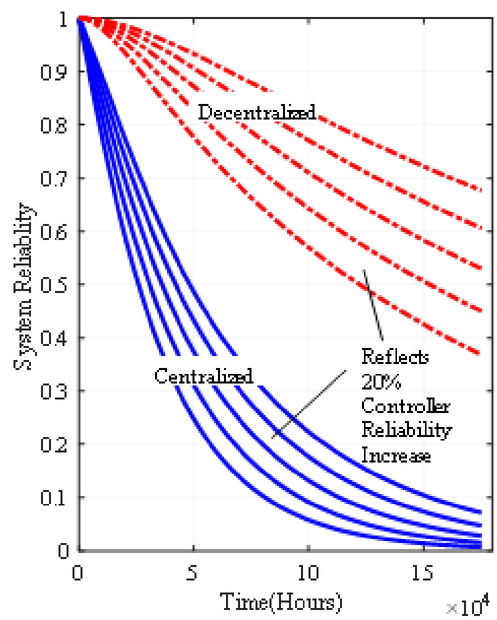

Figure 8. Microgrid system reliability curve assuming no repairs

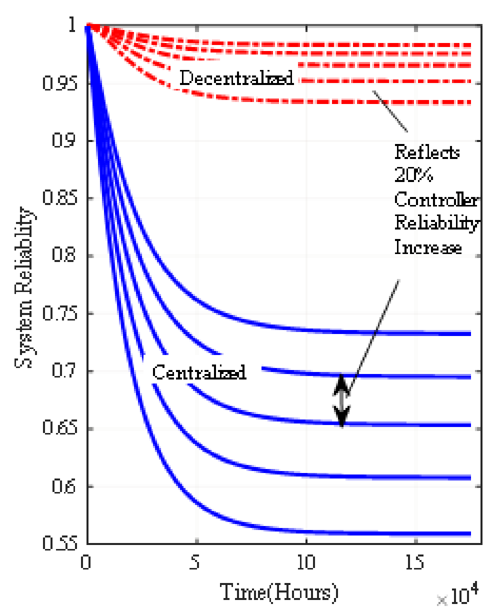

Figure 9. Microgrid system reliability curves (repairable system).

which is one of the future aspects to study using the proposed platform. Accurate model interaction between power system components and loads with various control topologies is also a preferred feature in simulation that is available in PSCAD. Microgrid controls in this platform are developed using the real-time module of the CompactRIO from National Instruments. Its capability to run in real-time interface mode serves the purpose of the platform.

B. Microgrid Normal Operation

For the proof-of-concept purposes, one scenario for normal operations is considered. The microgrid operates in island mode, energy storage regulates the voltage and frequency of the bus during the transition period. Figure 11 shows the active power curves captured over 130 seconds period. The system simulation starts with fully charge Energy Storage (ES). Natural Gas generator 1 (NG1), Natural Gas generator 2 (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; Decentralized Microgrid Controller (DMGC) of NG1 commands NG1 to start and synchronize with the bus, and commands the breaker after 6 seconds providing 190KW (at 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 switches to charging mode.

C. Controller Failure Impact

One of the advantages of using HIL platform is the capability of configuring and injecting failures at the hardware and/or software level. Since the scope of this paper is the failure of the controller; failing a controller is performed by powering down the controller, or resetting the controller manually. Two test cases have been performed in order to validate the impact of failures in the control system: 1) failing the central controller in a centralized architecture. 2) failing one decentralized controller. The conducted test cases do not represent the most extreme cases, but they were chosen as they occur during transient periods. These cases may have low probabilities to occur, but the reliability analysis in section IV were simulated for over 10-year period.

Figure 12 illustrates a scenario where the central controller of the microgrid fails during islanded mode. For this case, at t=9s controller commands NG1 and NG2 to connect as the SOC of the ES is low (as in subsection B), during the transition the controller fails, at t=11s. As a result of this failure, bus voltage and frequency become unstable, and converge to undesired levels. This scenario forces the microgrid to shut down.

Decentralization of a control system comes with additional overhead algorithm in response to failures. Generally, a rule based decision making algorithm is executed in this case in order to support the objectives of microgrid operations (frequency, voltage, critical loads). The responses of the decentralized controllers should insure fast transition after the failure occur.

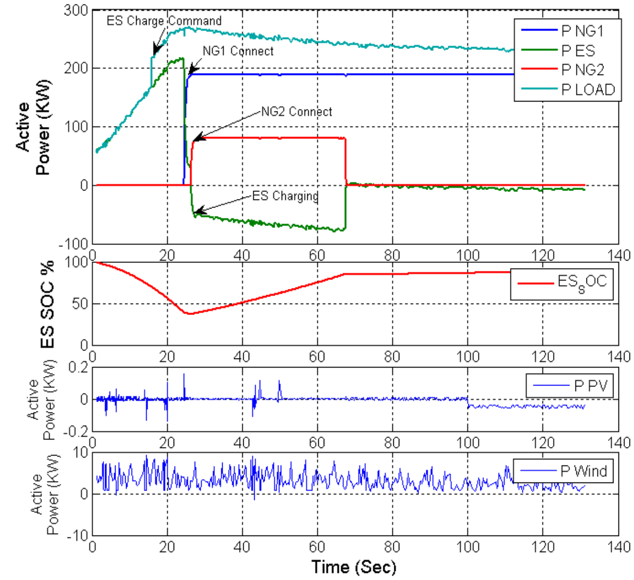

Figure 11. Normal operation of decentralized microgrid control architecture.

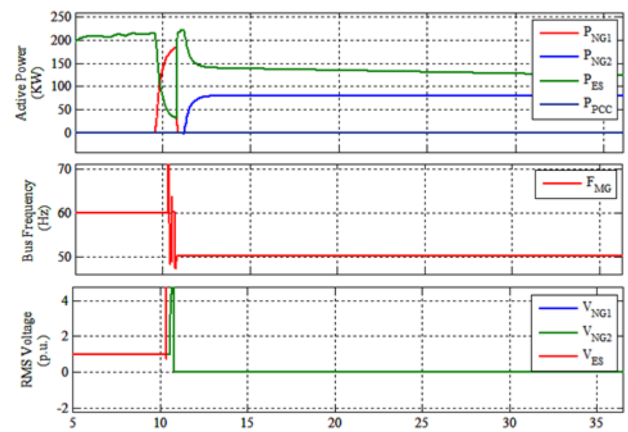

Figure 12. Impact of failing microgrid central controller on bus voltage and frequency.

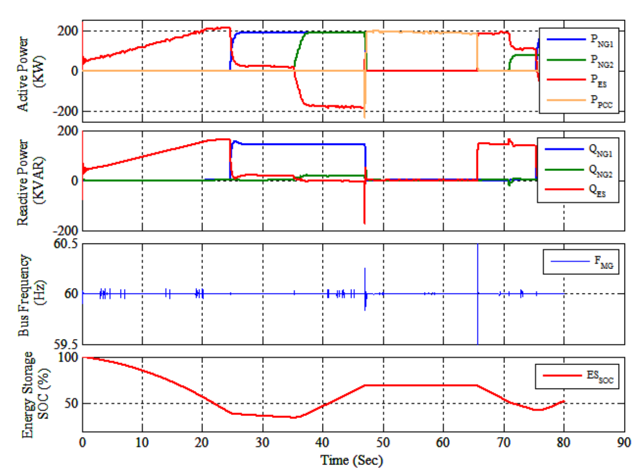

Figure 13. Impact of failing one decentralized controller on microgrid operation.

Figure 13 illustrates the case of failure of one decentralized controller, the failing controller for this case is the NG1, which could be one of the extremist cases since the generator may be responsible regulating the bus voltage/frequency at the time of failure. At t=47.5, the controller of NG1 fails while both generators are running and the ES is in charge mode. Two controllers can respond fast to this change, ES controller can command ES to take over, or the PCC controller can command emergency grid connection. For this case, PCC responded since the SOC of the battery is critically low. NG1and NG2 are shut down. One other case where microgrid needs to remain in islanded mode, NG2 can remain running but load shedding can be performed until the failure clears [2]. 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.

V. Conclusion

Microgrids are considered a solution to reliability enhancement of distribution systems. As a vital investment, reliability of microgrids becomes a challenge when various technologies are integrated. This paper investigated the reliability measures of microgrid control architectures. Reliability models of centralized and decentralized architectures were analyzed and demonstrated using HIL platform. Results show that decentralization of microgrid control architecture improves the reliability as the single point of failure is eliminated in centralized architecture. Challenges arise when decentralized architectures are adopted, controller to controller synchronization and certain levels of intelligence is needed to achieve optimized performance and protection. Cyber-security concerns emerge as communication links are essential for optimal performance. Interdisciplinary Research on decentralization is necessary comprising research fields of software, hardware, and communications. Future efforts include diagnostic algorithms and resiliency of the control architecture is still needed, considering the primary control level.

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