Coordinated Frequency and Voltage Regulation of Grid-Following and Grid-Forming Inverters

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Abstract—In this work, we propose a peer-to-peer secondary control for voltage and frequency regulation in islanded microgrids to facilitate high inverter-based distributed energy resource (DER) integration in the distribution grid. It has been a major challenge to achieve various performance objectives simultaneously in an inverter-driven microgrid, i.e., system frequency restoration, real power sharing, voltage regulation and circulating var mitigation. We show that the challenge can be addressed in even microgrids with 100% penetration of inverters, without the support of any synchronous generators or the bulk power system. In specific, we propose a novel control scheme to coordinate a fleet of grid-forming and grid-following inverters by using a leader-follower consensus algorithm to achieve these objectives simultaneously. Several use cases examining the effects of microgrid switching events (topology change) and communication degradation are presented to demonstrate the effectiveness of the proposed control architecture.

Index Terms—Inverters, DER, grid-forming, grid-following, consensus, frequency stability, voltage regulation, power sharing.

I. INTRODUCTION

Power system are experiencing a historical paradigm shift from being driven by predominantly rotating machine-based generation to inverter-based generation. The reduced inertia due to inverter-based generation can significantly compromise the power system’s stability and security. Therefore, one of the key requirements for transitioning to an electrical grid with high inverter penetration is to efficiently exploit inverters’ capability to respond to changes in frequency/voltage and help stabilize the grid against disruptions. Recently, microgrid has emerged as a technology to facilitate this transition [1], [2].

Firstly introduced in [3], a microgrid is defined as a group of interconnected loads and DERs within clearly defined electrical boundaries that acts as a single controllable entity and can operate while connected to a grid or in autonomous/islanded mode [2]. A microgrid has potential to provide energy surety to all critical facilities and services, improve the reliability of power grids during extreme events, and can evolve as a key building block for the future power grid [4]. However, microgrids can experience disturbances under abrupt events like microgrid islanding, load changes, or resynchronization. In the islanded mode, voltages and frequency of the microgrid are no longer supported by a host grid, and thus they must be controlled by different DERs. Also, critical demand-supply equilibrium requires accurate load sharing mechanisms to balance sudden real power mismatches caused by abrupt events. Therefore, to support high penetration of inverters in microgrids, it is imperative that the inverters-based DERs can cooperatively ensure frequency and voltage regulation, power balance, and load sharing in the network.

On the control aspect, various control strategies have been proposed to address these challenges and have subsequently been aggregated into a hierarchical control architecture [4], [5], which include three levels with different functions: (i) the primary control stabilizes the microgrid and establishes power sharing; (ii) the secondary control removes the deviations in both global frequency and local voltages from the nominal values; (iii) the tertiary control is concerned with global economic dispatch over the network and depends on current energy markets and prices. Traditionally, all of these control levels can be implemented in a centralized control architecture [5]. However, this centralized control architecture do not have the flexibility or the scalability to integrate the increasing number or variety of DER devices, because the control center needs to update whenever a new DER device is integrated. Also, the centralized control architecture requires for long communications links, leads to decision delays, and a failure at the control center in extreme events may disrupt the whole system. Therefore, to enable large scale integration of DERs in power systems, it is necessary to look at either local or peer-to-peer control architecture for inverters control.

Currently, the standard primary control employs proportional control loops implemented locally at each inverter, which only relies on local measurements and requires no communication [6], [7]. However, local control is not suitable for addressing the system-level objective in the secondary control level, since the local controls work without cooperation and can conflict with each other. As such, much effort has been pursued on peer-to-peer control architecture for the secondary control [8], [9]. Here, each inverter sends the local measurement signal to its neighboring inverters (i.e., inverters those it has communication with), and then adjusts its dynamics based on the differences between its signal with its neighboring inverters’ signal. Unlike the centralized control, the peer-to-peer control architecture reduces computational resources and allows for plug-and-play integration of DERs (since it does not require the control center to update whenever a new DER device is integrated). This control architecture was applied for the secondary control of both frequency and voltage in islanded microgrids [9]. In parallel, peer-to-peer architecture has been evaluated for the energy and power trading in the tertiary control level as well [10].

On the the power electronics aspect, the DER inverters are usually of two types, namely grid-forming (GFM) and grid-following (GFL) [11], [12]. The GFL inverters have
capability to control the output current magnitude and phase angle and thus can regulate the real power and reactive power (var) output [13], [14]. The GFL sources cannot directly regulate system voltage and frequency and behave more like a negative load than a traditional source with inertia. Whereas GFM inverters can directly control voltage and frequency and behaves as a controllable voltage source behind a coupling reactance, which is much like a synchronous generator [15].

One major limitation of the existing works in peer-to-peer voltage and frequency control in microgrids is that they only consider GFM inverters and no GFL inverters. The underlying reason is that GFL inverters cannot directly control the frequency and voltage, but follow the measured frequency and voltage. However, it is important to note that most of the inverters in practice are of GFL type. The uncooperative real power and var output from dominant GFL inverters can degrade the frequency and voltages of the microgrid. Therefore, to promote large scale integration of DERs, it is necessary to leverage both GFM and GFL inverters in the frequency and voltage regulation. In the literature, the GFL-GFM coordination to fulfill these objectives has not been explored yet.

In this paper, we use a leader-follower consensus (LFC) control architecture to coordinate between GFM and GFL inverters with the former being leaders and the latter being followers. The objective is to simultaneously achieve a fast frequency and voltage regulation along with accurate real power and var sharing among all inverters under various disturbances. Unlike [8], [9], the distinction of our work is that we consider both GFM and GFL inverters for frequency and voltage regulations. In addition, rather than a standard consensus algorithm as in [8], [9], our work utilize a leader-follower consensus algorithm which exploits the physical characteristics of GFM-GFL inverters: (i) the GFM inverters directly control frequency and voltage, and hence, serve as leaders, (ii) the GFL inverters measure frequency/voltage to modulate their outputs, and hence, they should serve as followers. We demonstrate the effectiveness of the proposed leader-follower control architecture on a networked microgrid test system under several switching and communication degradation events. In particular, we show that the proposed leader-follower control is robust to switching communication degradation events, while outperforming both local secondary control and the absence of secondary control in terms of power sharing and frequency/voltage regulations.

The structure of this paper is as follows. In Section II we describe the detailed models of GFM and GFL inverters equipped with standard droop primary controls. Section III introduces the leader-follower control framework for frequency/voltage regulation and power sharing among GFM-GFL inverters. In Section IV we present the co-simulation framework and use cases to validate the effectiveness of this consensus framework. Conclusions follow in Section V.

II. MODELING OF GRID-FORMING AND GRID-FOLLOWING INVERTER PRIMARY CONTROL

A typical 3-phase voltage-source inverter equivalent circuit and its interface to a distribution grid via a filter impedance is shown in Fig.1 [12]. The internal magnitude \( E_g \), \( E_b \), \( E_c \) of the inverter and their corresponding phase angles \( \delta_g \) are regulated by an inverter controller that takes grid voltage \( V_g \angle \delta_g \) and current \( I_g \angle \phi_g \) measurement as inputs. The controller can either be GFM or GFL as described below.

A. Grid-Forming (GFM) Control

An inverter with GFM control can be modeled as an AC voltage source behind a coupling impedance that can generate a desired constant voltage magnitude and frequency in an isolated microgrid as shown in Fig.2 [12]. Mathematically, it can be represented as following for an \( i^{th} \) inverter:

\[
\dot{\delta}_i = u_i^\delta \quad (1) \\
E_i = u_i^V \quad (2) \\
P_i^m = P_i + \tau_p \dot{P}_i \quad (3) \\
Q_i^m = Q_i + \tau_q \dot{Q}_i \quad (4)
\]

where \( u_i^\delta \) and \( u_i^V \) are frequency and voltage control inputs to the inverter. Real and reactive power output measurements \( P_i^m \) and \( Q_i^m \) are processed through low pass filter with time constant \( \tau_p \) and \( \tau_q \) respectively to obtain filtered quantities \( P_i \) and \( Q_i \). In order to enable parallel operation of grid forming inverters, several primary control strategies have been proposed such as virtual oscillator [16], virtual synchronous machine [17] and, droop controls [18], [19]. However, in this work, we choose a relatively well tested CERTS power-frequency \((P-f)\) droop and var-voltage \((Q-V)\) droop control as primary controls [3], [12]. \( P-f \) and \( Q-V \) droop controls regulate the frequency and inverter terminal voltage according to (5) and (6) respectively.

\[
u_i^\delta = \omega = \omega^{nom} - m_p (P_i - P_i^{set}) \quad (5) \\
V_i = V_i^{set} - m_q (Q_i - Q_i^{nom}) \quad (6)
\]
where \( P_i^{\text{set}} \) and \( V_i^{\text{set}} \) are real power and voltage set-points respectively and \( m_p \) and \( m_q \) are the droop gains. \( \omega_i^{\text{nom}} \) and \( Q_i^{\text{nom}} \) are nominal frequency and reactive power, usually taken as 60 Hz and 0 respectively. Here it should be noted that we are interested in regulating inverter terminal voltage \( V_{g_i} \) rather than \( E_i \). Therefore, the \( Q-V \) droop controls \( V_i \) that is an average inverter terminal voltage across all phases i.e. \( V_i = (V_g^a + V_g^b + V_g^c)/3 \). Voltage control input \( u_i^V \) is obtained by passing \( V_i \) through a PI controller as described in [12].

A typical CERTS P-f and Q-V droop curves are shown in Fig.3a and Fig.3b respectively. The main purpose of P-f droop is to enable multiple inverters to share real power. Q-V droop helps in mitigating circulating var among paralleled inverters.

### B. Grid-Following (GFL) Control

GFL control enables an inverter to behave like a current source that can inject a specified real power and var into the grid as shown in Fig.2b. GFL control measures the frequency and voltage to provide desired \( P_i \) and \( Q_i \) via a phase-locked loop (PLL) and current control loop. Current control loop is modeled in d-q reference frame as \( I_{d_i} \) and \( I_{q_i} \) respectively and can be mathematically written as,

\[
I_{d_i} = u_{i_d}^P \\
I_{q_i} = u_{i_q}^P \\
\omega = \delta_i^{\text{PLL}} \\
\delta_i^q = \delta_i^{\text{PLL}} + \tau f \delta_i^{\text{PLL}} \\
V_i^m = V_i + \tau v \dot{V}_i
\]

where \( u_{i_d}^P \) and \( u_{i_q}^P \) are real and reactive power control inputs for inverter current in d-q reference frame defined as following: 

\[
u_{i_d}^P = P_i/V_i^d \\
u_{i_q}^P = Q_i/V_i^d
\]

where \( P_i \) and \( Q_i \) are desired real and reactive power signals. \( V_i^d \) is d-axis voltage in d-q reference frame and can be defined as \( V_i^d = V_i \cos \delta_i^{\text{PLL}} \cos \delta_i^q \). PLL can be modeled as a low-pass filter with time constant \( \tau_f \) that estimates the grid side voltage angle \( \delta_i^q \) as \( \delta_i^{\text{PLL}} \). Similarly, voltage measurements \( V_i^m \) is processed through low pass filter with time constant \( \tau_v \) to obtain filtered quantity \( V_i \). The output current is controlled in d-q reference frame via a PI controller. The detailed description of PLL and current control loop can be obtained from [12].

In GFL, usually an external grid support function is added to indirectly regulate voltage and frequency [14]. In this work, we use DER integration standard IEEE1547-based volt/var and freq/watt droop controls as grid support functions and primary control for GFL inverters as following:

\[
P_i = P_i^{\text{set}} + (\omega_i^{\text{nom}} - \omega)/m_p \tag{14}
\]

\[
Q_i = Q_i^{\text{nom}} + (V_i^{\text{set}} - V_i)/m_q \tag{15}
\]

A typical freq/watt and volt/var droop functions are shown in Fig.3c and Fig.3d respectively.

Essentially, the main purpose of primary droop controls in both GFL and GFM is to provide an instantaneous frequency and voltage regulation by sharing the load. However, due to their proportional nature, the accurate regulation can not be achieved as they always end up with a steady state deviation in both frequency and voltage. A coordinated secondary control is needed to accomplish removal of these errors.

III. LEADER-FOLLOWER CONSENSUS ARCHITECTURE FOR FREQUENCY AND VOLTAGE REGULATION

A special type of consensus framework, namely leader-follower (LF), will be utilized in this section to implement the peer-to-peer control for a fleet of GFL and GFM inverters as secondary control. In the standard consensus framework, multiple agents aim to reach an agreement on some decision/values by exchanging information among agents and then each agent adjusts its dynamics or behavior based on the information from the agents those it communicate with [20]. In the LF framework, one or more agents are selected as leaders with external inputs in addition to the consensus protocol, while the remaining agents are followers only obeying the consensus protocol [21].

Mathematically, a group of agents can be denoted as \( A = \{1, 2, ..., n\} \), in which the first \( n_f \) agents are selected as followers while the last \( n_l \) agents are selected as leaders with respective notions \( A_F = \{1, 2, ..., n_f\} \), \( A_L = \{n_f + 1, n_f + 2, ..., n_f + n_l\} \) and \( n = n_f + n_l \). Consider \( N_i \) as the set of agents that communicate with agent \( i \). For simplicity, let \( x_i \in R \) be the position of agent \( i \), where we only consider the one dimensional case, yet the framework can be extended to higher dimensions. The state evolution of each follower \( i \in A_F \) is governed by the first order consensus protocol:

\[
\dot{x_i} = \sum_{j \in N_i} (x_j - x_i), \ i \in A_F, \tag{16}
\]

while the state evolution of each leader \( i \in A_L \) is governed by the first order agreement protocol with an assigned external input \( u_i \in R \):

\[
\dot{x_i} = \sum_{j \in N_i} (x_j - x_i) + u_i, \ i \in A_L. \tag{17}
\]
The external control input $u_i$ can be designed to achieve additional control objectives, e.g., ensuring the agents reach to the agreement in one predefined way [22].

Since GFM inverter control actively sets the frequency and voltage whereas GFL control measures them to modulate its output, their combination naturally fits the leader-follower architecture, in which GFM inverters serve as leaders and GFL inverters serve as followers. Consider a microgrid network with $N_L$ GFL and $N_M$ GFM inverters represented by sets $L = \{1, 2, 3, \ldots, N_L\}$ and $M = \{N_L + 1, N_L + 2, N_L + 3, \ldots, N_L + N_M\}$ respectively, with total number of inverters denoted by $N = N_L + N_M$. The communication link pattern among the inverters can be represented by an $N \times N$ adjacency matrix $C$, with elements $c_{ij}$, i.e., $c_{ij} = 1$ if the communication exists between inverter $i^{th}$ and $j^{th}$, and $c_{ij} = 0$ otherwise. In the next section, we apply the leader-follower concept to design secondary controller for GFL and GFM inverters.

A. Frequency regulation and real power sharing

There are two objectives to achieve while designing secondary control for $P$-$f$ and freq-watt droop controls i.e. frequency restoration to nominal and equal real power sharing among inverters. To accomplish this, we propose following secondary control for GFL [18] and GFM [19]:

$$-k_i^p \frac{dP_i^{set}}{dt} = \sum_{j \in N_i} c_{ij}(m_i^p P_i - m_j^p P_j), \forall i \in L \quad (18)$$

$$-k_i^q \frac{dP_i^{set}}{dt} = (\omega_i - \omega^{nom}) + \sum_{j \in N_i} c_{ij}(m_i^q P_i - m_j^q P_j), \forall i \in M \quad (19)$$

Here, $k_i^p$ is a positive gain for $i^{th}$ inverter and affects the speed of frequency regulation. $P_i^{set}$ from primary controls is utilized as secondary control variable. $m_i^p P_i$ can be considered as a real power sharing factor for an inverter. Following leader-follower concept, both GFL and GFM have real power sharing terms whereas only GFM has an extra frequency restoration term in [19]. Thus, (5)+(19) and (14)+(18) make a complete frequency control for GFM and GFL respectively. Note that with no communication, this control will be an equivalent of frequency restoration without ensuring power sharing what we term as local secondary control.

B. Voltage regulation and reactive power sharing

Similar to previous section, we have two objectives here i.e. voltage regulation and mitigating circulating reactive power by equal sharing. However, unlike frequency regulation and real power sharing, it is not possible in general to achieve both the objectives accurately. We can achieve the desired internal voltage $E_i$ but terminal voltage $V_i$ is impacted by network impedance. Therefore, an equal var sharing has an inherent conflict with the accurate voltage regulation in parallel inverter operations as observed and explained by [9], [23]. Therefore, we design a compromise between two objectives as following:

$$-k_i^q \frac{dV_i^{set}}{dt} = \sum_{j \in N_i} c_{ij}(m_i^q Q_i - m_j^q Q_j), \forall i \in L \quad (20)$$

Here, $k_i^q$ is a positive gain and $V_i^{set}$ is a secondary control variable from primary controls. $V_i^{nom}$ is a nominal voltage usually taken as 1 pu. $m_i^q Q_i$ can be considered as a var sharing factor for an inverter. The trade-off between voltage regulation and var sharing is implemented by scaling coefficients $\alpha$ and $\beta$ for GFM in [21]. The tuning of the scaling coefficient will depend on the network and utility requirements. The tuning can also be made adaptive, though we use a offline tuning in this study. Thus, (6)+(21) and (15)+(20) make a complete voltage control for GFM and GFL respectively. Note that the local secondary version of this control with no communication will be an equivalent of accurate voltage regulation with high circulating var.

IV. CO-SIMULATION FOR VALIDATION

We develop a co-simulation platform as presented in Fig. 4 in which the secondary peer-to-peer controllers are programmed in Python to send control action to the respective DER inverters. The microgrid modeling and inverter dynamics are simulated in GridLAB-D [24]. An open-source middleware HELICS [25] is used to handle the data exchange between GridLAB-D and the Python-based controllers, and to maintain time synchronization between the individual programs.

A modified and fully inverter based IEEE 123-node test feeder is used to demonstrate the impact of the proposed LFC
As shown in Fig. 6, it is a networked microgrid test system in which three microgrids (shown in the shaded area) are interconnected via switches $sw_1$, $sw_2$, and $sw_3$. There are total 9 utility-scale inverters installed in the system out of which 6 are GFL and 3 are GFM inverters. The locations and ratings of the inverters are listed in Table I. Note that each microgrid has 1 GFM and 2 GFL inverters. The total rating of the inverters is around 3900 kW, and the peak total load in the networked microgrid is about 3500 kW. All inverters have 1% frequency droop and 5% voltage droop values. In order to test the control performance in a very low-inertial microgrid, there is no generator installed in the system.

A. Frequency Regulation Case Study Results
To evaluate the comparative performance of the proposed control, three cases are studied with different control strategies as following: (a) Case I, where only primary droop control is deployed with no secondary control; (b) Case II, in which local secondary control is deployed with no communication between inverters; (c) Case III with proposed LFC control. To begin with, at $t = 0$, the whole system is connected to the grid via substation. At $t = 1$, the networked microgrid (shaded area) is isolated from the rest of the system and substation by opening switch between bus 13 and 152. At $t = 4$, a load disturbance is simulated by opening switch between bus 60 and 160 that disconnects around 1200 kW load (35%). Fig. 6 captures the frequency and real power response of these events in all three cases. Fig. 6a-6c show the simulation results for Case I i.e. no secondary control. It can be seen that at $t = 1$ (islanding), all inverters need to increase their generation level according to their droops (Fig. 6d) that leads GFM inverter frequency a lower value of around 59.86 Hz (Fig. 6a). Similarly, at $t = 4$ the load reduction leads to reduction in inverter generation levels and corresponding frequency increase to above nominal. In both disturbances, power sharing among all inverters is maintained. It can be verified from Fig. 6c that shows the power sharing
factors for all inverters converging to the same value after initial transients.

Similar analysis of Case II in Fig. [6g] reveals the importance of coordination between GFM and GFL in frequency restoration. It can be seen in Fig. [6f] that both GFL and GFM instantly responds to frequency disturbance at \( t = 1 \) and share power but as frequency starts restoring towards nominal, GFL power level also returns to its nominal as they follow the frequency unlike GFM which set the frequency. Consequently, GFM inverter has to compensate the required generation. In this particular case, the required compensation exceeds the GFM inverter rating and thus frequency is not restored fully. Moreover, power sharing is also not maintained among inverters. After load reduction at \( t = 4 \), GFMs are able to restore the frequency back to nominal, however it results in highly skewed power sharing due to lack of communication.

Finally, the proposed leader-follower control performance (Case III) can be seen in Fig. [6i]. In this case, after both the disturbances at \( t = 1 \) and \( t = 4 \), the frequency restores to nominal 60 Hz as well as equal power sharing is achieved among all 9 inverters within less than 0.5 seconds. The frequency nadir (minimum post-contingency frequency) is also improved compared to case I. Unlike case I and II where only one of the objectives are met, the proposed control is able to achieve both power sharing and frequency restoration fast enough with GFL-GFM combinations.

B. Voltage Regulation Case Study Results

Fig. 7 compares the voltage regulation and var sharing among inverters in the aforementioned 3 cases. The voltage regulation is evaluated by calculating a mean absolute error (MAE), defined as

\[
MAE = \frac{\sum_{i=1}^{T} \sum_{j=1}^{N} |V_{ij} - 1|}{T \cdot N}
\]

where \( T \) and \( N \) denote the time duration and number of inverters. On investigating Case I, we observe that the after islanding at \( t = 1 \), primary droop controls are not able to bring voltages to nominal 1 pu as can be seen in [7a]. As discussed before, due to line impedance effect, equal var sharing among inverters is not achieved, though they are close to each other as can be seen in [7c]. At \( t = 4 \), the voltages comes closer to nominal voltage due to a favorable disturbance i.e. load reduction. A similar analysis of Case II reveal that local secondary control of GFM is able to improve voltage regulation significantly (Fig. [7d]), however it leads to a very high amount of circulating var or skewed var sharing among inverters as can be seen in Fig. [7f]. The lack of communication...
and push for a very high voltage regulation leads to this undesired response. The proposed LFC control in Case III arrive at a compromise between voltage regulation and power sharing as shown in Fig.9f and Fig.10b where voltages are relatively closer to nominal voltage without resulting in high circulating var as in Case II. As in Table II, the voltage mismatch error in the proposed LFC is 0.002 pu which is not as good as case II due to better var sharing performance but significantly (5 times) better than the case I.

C. Impact of Reduced Communication and Link Failure

In order to test the robustness of the proposed control with reduced communication, each microgrid is considered as one cluster with one leader GFM inverter. The communication across these clusters is only maintained through leader GFMs i.e. inverter 1, 4, and 7 and all other communication across the clusters are disabled. Further, an event of communication link failure between leader GFM 4 and 7 is applied at $t = 4$ seconds. Frequency and voltage response in this case can be seen in Fig.10c. It can be noticed that even with the reduced communication, the controller performance for frequency restoration is very close to the results in Fig.8c except the fact that the power sharing convergence takes little more than 0.5 seconds as shown in Fig.10d. Similarly, a good voltage regulation is achieved under reduced communication as shown in Fig.10e. An interesting observation can be made in Fig.10f that an var sharing is improved among the inverters within the same cluster and is slightly worsened across the clusters. This is due to change in the communication pattern i.e. reduced communication across the clusters.

D. Controller performance under microgrid switching

Finally, the controller performance has been tested in an event of microgrid switching in a networked microgrid as shown in Fig.5. At $t = 4$ seconds, switches $sw 1\_2$ and $sw 2\_3$ are opened so that all 3 microgrids become isolated networks, each with 1 GFM and 2 GFL inverters. Fig.5 show the frequency and power sharing response for such case. It can be seen that at $t = 4$, all 3 GFM have different transient response but settle back to nominal frequency. GFM inverter 4 of microgrid 2 goes through the highest frequency transient peak due to largest adjustment in power generation level as can be verified in Fig.8c Fig.8d show how each microgrid achieves its own power sharing level among its inverters after switching out from a common power sharing in a networked microgrid. The results show the quick adaptability of the proposed controller in a emerging networked microgrid scenarios. Similarly, Fig.9c shows a good voltage regulation performance after $t = 4$ in all 3 isolated microgrids. An interesting observation can be made in Fig.9d where all 3 microgrids have an accurate equal var sharing along with achieving a very good voltage regulation. This is possible because of the electrical proximity all 3 inverters within each microgrid.

V. Conclusions

This paper presents a secondary frequency and voltage regulation for a fleet of GFL and GFM DERs in isolated microgrids and networked microgrids. By using a leader-follower architecture on both GFM and GFL inverters, where the GFM inverters serve as leaders and GFL inverters serve as followers, we obtained the accurate power sharing among all inverters, while ensuring that the frequency of the system will return back to the nominal value after the system experiences disturbances. Similarly, the proposed control improves the voltage regulation while keeping circulating var in limit. We showed that this peer-to-peer control is robust to communication failure and different switching events such as microgrid isolating and abrupt load changes.

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Fig. 8. Impact of reduced communication and a communication link failure on frequency and voltage regulation and power sharing response of proposed leader-follower control.

Fig. 9. Leader-follower control performance in the event of multiple microgrid switching in a networked microgrid system.