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Peer-to-peer Communication Control Architecture for Engaging Ubiquitous DERs to Support Distribution System Resiliency

July 2021

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Ankit Singhal

U.S. DEPARTMENT OF ENERGY

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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]. 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 experiences 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 demandsupply 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 does 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-topeer 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 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 GFLGFM coordination to fulfill these objectives has not been explored yet.

In this project, we developed 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 inveters for frequency and voltage regulations. In addition, rather than a standard consensus algorithm as in [8], [9], our work utilized 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. The effectiveness of the proposed LFC coordination was tested on a networked microgrid test system under different disturbances and communication degradation events. We demonstrated that the proposed fully coordinated control is robust to disturbances, while outperforming uncoordinated and GFM-only coordinated approaches. Overall, this work emphasized the necessity and benefits of the GFM-GFL coordination in the secondary control of microgrids.

From this project, we submitted a journal manuscript to the IEEE Transactions on Smart Grid. It is currently under review and revision. An online version of the paper can be assessed here: https://arxiv.org/abs/2012.06685
In this online version, we provided more details of the proposed leader-follower control framework for secondary control of grid-forming and grid-following inverters. The foundational peer-to-peer communication control developed in this paper is also being leveraged in the GMLC Citadels project.

Demonstration

We demonstrated the effectiveness of the proposed leader-follower control architecture on a networked microgrid test system, in Fig. 1, under several switching and communication degradation events. As shown in Fig.1, it is a networked microgrid test system in which three microgrids (shown in the shaded area) are interconnected via switches sw 1 2 and sw 2 3. There are total 9 utility-scale inverters are installed in the system out of which 6 are GFL and 3 are GFM inverters. Note that each microgrid has 1 GFM and 2 GFL inverters. The total rating of the inverters is about 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.

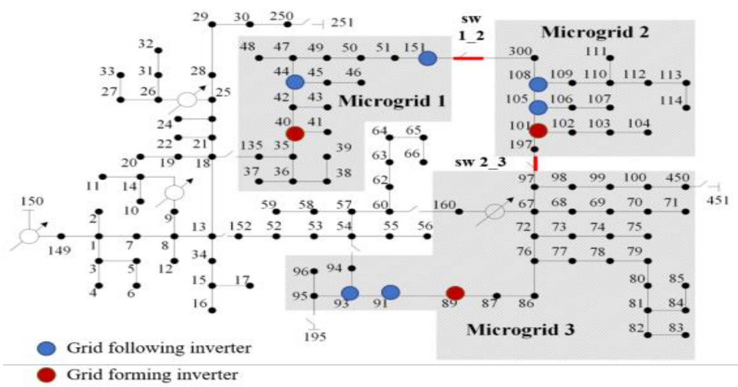


Fig. 1. A modified IEEE 123 test feeder to create a networked microgrid system

We used the co-simulation platform in Fig. 2, 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. In particular, we showed 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.

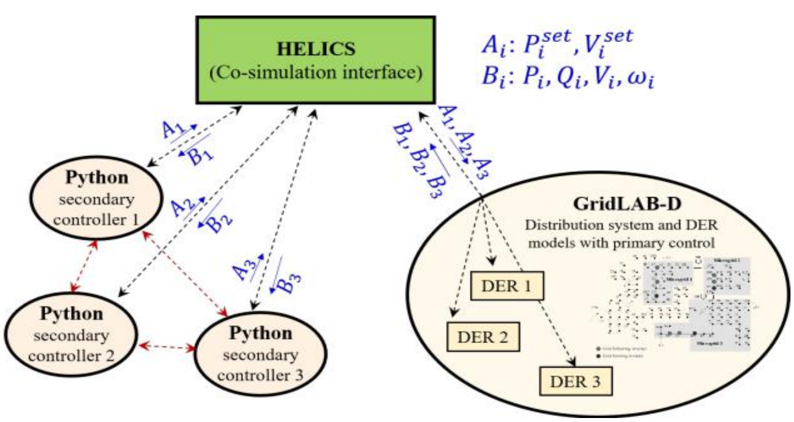
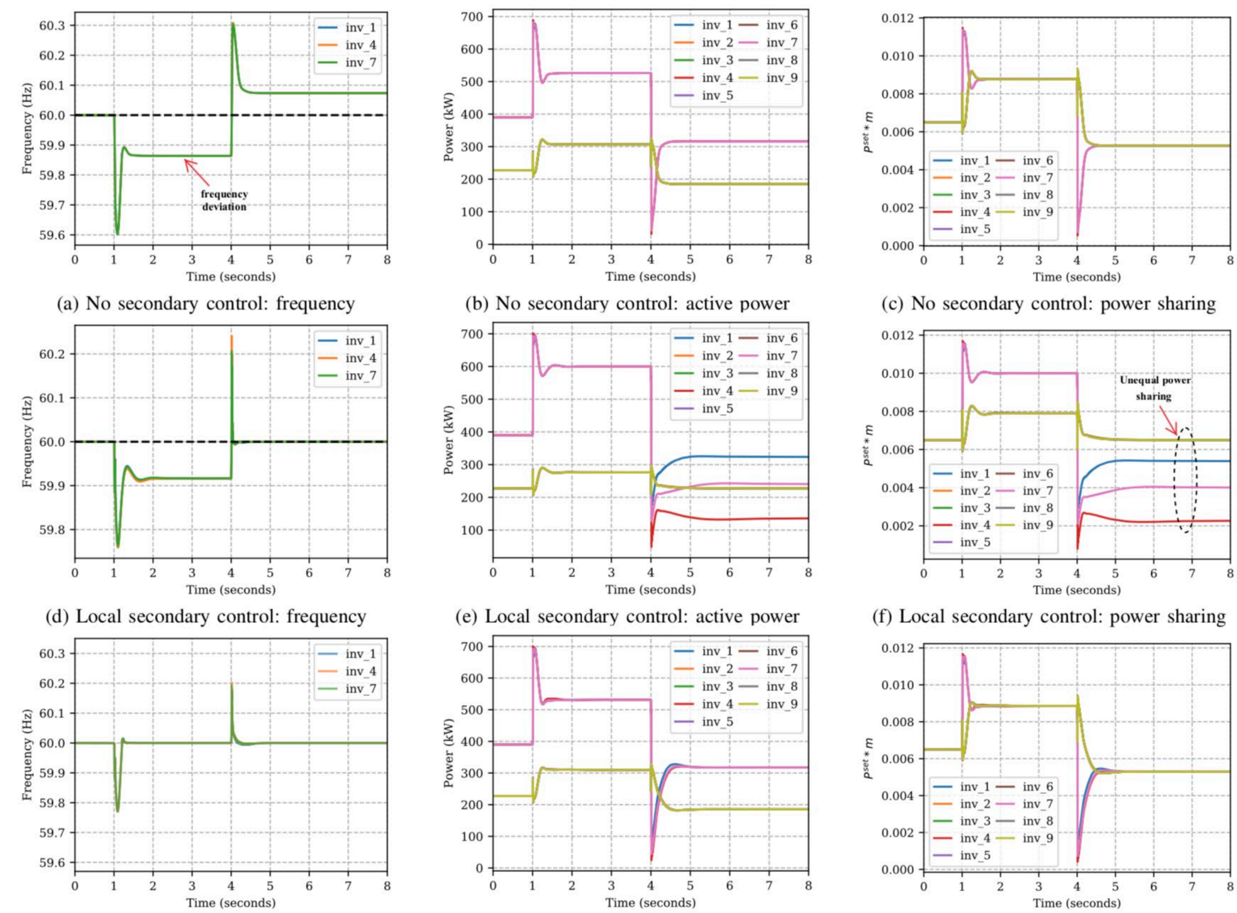


Fig. 2. Co-simulation platform for controlling of DERs in networked microgrids

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%).



(a) No secondary control: frequency (b) No secondary control: active power (c) No secondary control: power sharing

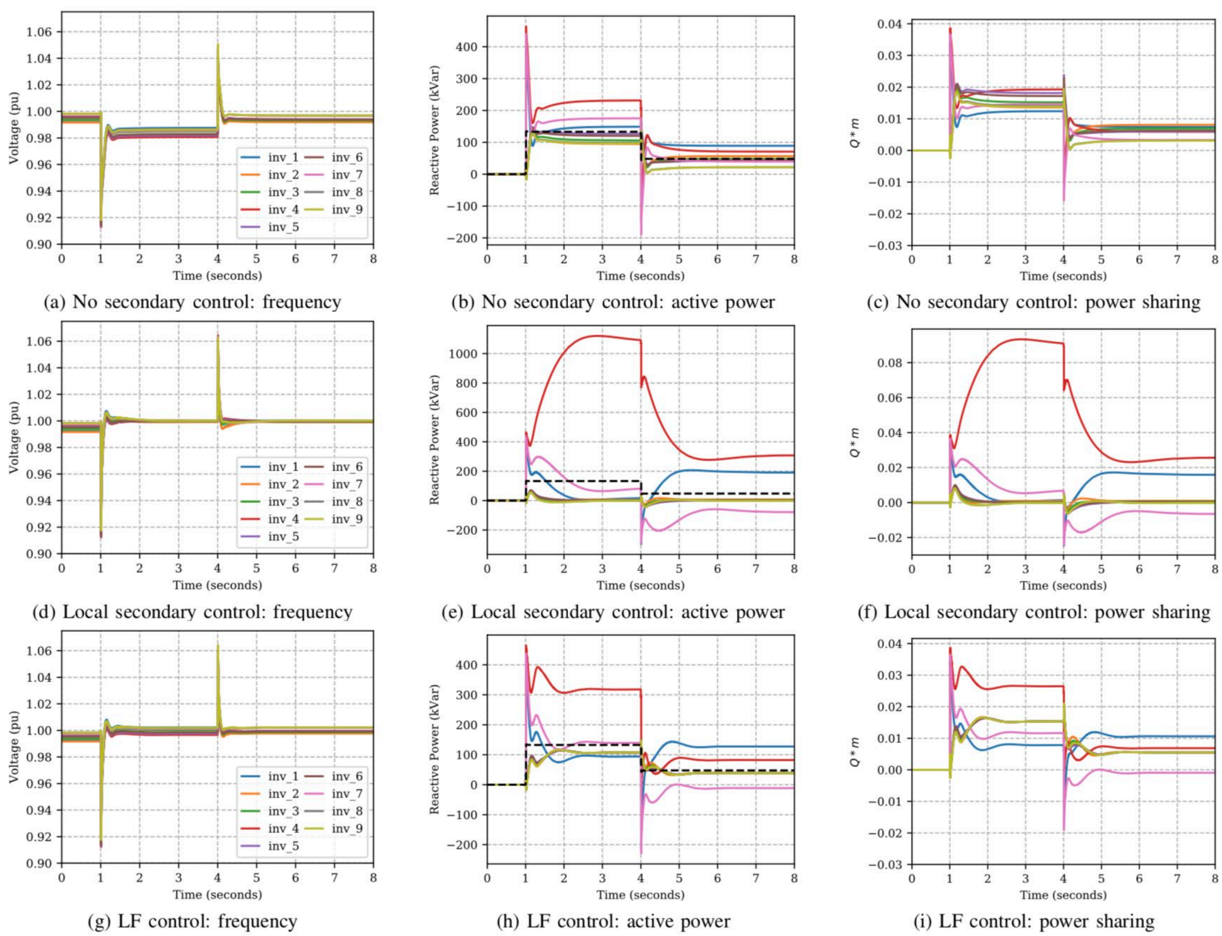
(d) Local secondary control: frequency (e) Local secondary control: active power (f) Local secondary control: power sharing

(g) LF control: frequency (h) LF control: active power (i) LF control: power sharing

Fig. 3. Comparison of the frequency response of the proposed control with no control and local control cases in the events of islanding and load disturbance

Fig.3 captures the frequency and real power response of these events in all three cases. Fig.(3a-3c) 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.3b) that leads GFM inverter frequency a lower value of around 59.86 Hz (Fig.3a). 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.3c that shows the power sharing factors for all inverters converging to the same value after initial transients. Similar analysis of Case II in Fig.3d - 3f reveals the importance of coordination between GFM and GFL in frequency restoration. It can be seen in

Fig.3e 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.3g-3i. 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.



(a) No secondary control: frequency
(b) No secondary control: active power
(c) No secondary control: power sharing
(d) Local secondary control: frequency
(e) Local secondary control: active power
(f) Local secondary control: power sharing
(g) LF control: frequency
(h) LF control: active power
(i) LF control: power sharing

Fig. 4. Comparison of the voltage response by proposed control with no control and local control cases in the events of islanding and load disturbance

Fig.4 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

$$MAE = \frac{\sum_{t=0}^{T}\sum_{i=1}^{N}|V_{i_t}-1|}{T.N}$$

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 4a. 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 4c. At t = 4, the voltages come 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.4d), however it leads to a very high amount of circulating var or skewed var sharing among inverters as can be seen in Fig.4f. 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 var sharing as shown in Fig.4g and Fig.4i 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.

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