On Control Schemes for Grid-Forming Inverters

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***Abstract* — Grid-forming inverters can collaboratively regulate the voltage and frequency of a microgrid. These inverters are expected to be seen more in the future microgrid, undertaking the roles of the conventional power generators. Like conventional power generators, they must balance supply and demand, contribute to power-sharing between inverters and other power generators, and restore the voltage and frequency after any power changes. These technical challenges are typically achieved through different primary and secondary controllers. This article reviews some state-of-the-art primary and secondary control schemes for the emerging technology of grid-forming inverters. First, the typical control schemes for grid-following inverters are briefly presented for the continuity of the discussion on the roles of the grid-forming inverters in future power-grid, followed by two basic control schemes for the grid-forming inverters. Then, two decentralized power-sharing techniques, i.e., droop, and virtual inertia, are analyzed. The technical challenges for inverter synchronization and some control methods are discussed afterward. Finally, several secondary control methods for the voltage and frequency restoration in grid-forming inverters are reviewed.**

Keywords—Grid-forming inverters, seamless reconnection, power-sharing, frequency, and voltage control.

I. INTRODUCTION

Grid-forming inverters will be widely used in future power grids [1]-[7]. Unlike grid-following inverters, which rely on the grid voltage and frequency references, the grid-forming inverters can independently generate their voltage and frequency references [8]. This independent characteristic is helpful for microgrids operating in islanded mode [9], [10] i.e., when the microgrid is disconnected from the main grid due to any anomaly, as the microgrid can reinstate its operation using the black-start capability of the grid-forming inverter [11], [12]. A cluster of microgrids, reinstated by groups of inverters, can collaborate to restore the utility grid after a black-out [13]. In a microgrid, not all the inverters must operate in grid-forming mode. Instead, a group of inverters can take the role of grid-forming while the others can operate in grid-following mode [14]-[17]. Typically, the inverters equipped with battery energy storage units, where the power source is not intermittent, are more suitable to operate as grid-forming units. Also, the capacity of the grid-forming inverters must be large enough to support the microgrid, especially immediately after a black-start. Nevertheless, the grid-forming inverters can be the microgrid’s primary power sources [17]. In such conditions, the inverters must mitigate the total active and reactive power demands [18]. Power-sharing between the inverters in proportion to the inverters' capacity is needed to avoid overloading any inverter [19]. Furthermore, the inverters must be able to regulate the microgrid’s voltage and frequency at any loading condition [13].

This article reviews some state-of-the-art primary and secondary grid-forming inverter control techniques for the islanded microgrid. The review focuses on basic inverter controls, control methods for decentralized power-sharing between multiple inverters, inverter synchronization methods, control techniques, and frequency and voltage restorations. The rest of the article is organized as follows. Section II reviews the typical grid-following control schemes for the continuity of the discussion on the future roles of the grid-forming inverters. Section III briefly presents two primarily used grid-forming inverter control methods. Decentralized power-sharing methods based on droop, and virtual inertia are reviewed in Section IV. Section V analyzes the synchronization methods for the inverters. Control techniques for voltage and frequency restoration are discussed in Section VI. Finally, section VII summarizes the findings.

II. CONTROL METHODS FOR THE GRID-FOLLOWING INVERTERS

This section reviews some common control methods for different grid-following inverters' roles in a grid standard. Currently, most inverters operate in grid-following mode, where the inverter's voltage is synchronized with the grid's voltage at the point of common coupling (PCC) while injecting active and reactive power into the grid. The synchronization process is established by using a phase-angle estimation technique, e.g., a phase-locked loop (PLL) or a phase-angle detector [20], [21]. In a typical grid-following controller, a current control loop is cascaded with the voltage control loop to control the active and reactive power injections. The controller can be configured to provide different ancillary services [22]-[24]. The inverter can curtail its active power injection and provide reactive power support to mitigate symmetrical and asymmetrical voltage sags [25], [26]. Negative-sequence compensation methods have been developed to offer ancillary services during asymmetrical anomalies in the grid [27], [28]. In [29], an atypical PWM control has been included in the controller so that the inverter can compensate for the dc-bus fluctuation. In [30] and [31], the controller can mitigate the voltage and frequency fluctuation by introducing adaptive piecewise droop in the controller. The controllers in [32] and [33] included virtual inductance to enhance the stability of the inverter in weak grids.

Future grid-forming inverters undertake the role of providing some ancillary services. This is possible in large grid-forming plants, i.e., a large photovoltaic plant with MW range of generation, with sufficient battery energy storage, where some grid-forming inverters can be operated for ancillary services.

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III. The Basic Grid-Forming Inverter Control Methods

The two most common grid-forming inverter control methods in this section, as shown in Fig. 1, have been reviewed. In grid-forming mode, the inverter can be viewed as a voltage source, controlling the voltage amplitude and frequency. Therefore, the primary controller only needs the voltage control loop. Notice that the primary controller also does not require any PLL to estimate the phase-angle of the voltage at the PCC.

As shown in Fig. 1, a nominal frequency, ω_n, is provided, and the PWM reference phase-angle, θ, is obtained from integrating the reference frequency, $\omega^* = \omega_n - \Delta\omega$. Here, $\Delta\omega$ can be calculated from the droop, see Fig. 1, or any other decentralized power-sharing topologies, e.g., virtual inertia. The PWM voltage reference, V can be obtained in two methods. Fig. 1(a) shows one topology, where the amplitude of the inverter output voltage, V, is controlled by minimizing the error between the desired voltage, $V^* = V_n - \Delta V$, and the amplitude of the measured voltage at the PCC, V_{PCC}. Here, V_n is the nominal voltage amplitude reference, and ΔV is the amplitude adjustment calculated from droop relationships, as shown in Fig. 1, or by any other decentralized power-sharing method. The proportional-integral block PI_V performs the voltage control. Fig. 1(b) shows another topology, where the q-axis component of the voltage reference, v_q^{inv}, is obtained by regulating the q-axis component of the PCC voltage, v_q^{pcc}, to the desired voltage reference, $v_q^* = V_n - \Delta V$, and the d axis component of the voltage reference, v_d^{inv}, is obtained by regulating the d-axis component of the PCC voltage, v_d^{pcc}, to 0. Two proportional-integral controllers, PI_{Vq} and PI_{Vd}, separately control the two PWM references. The component parameters are then converted from $dq0$ to abc frame of reference to generate the PWM signals [34], [35].

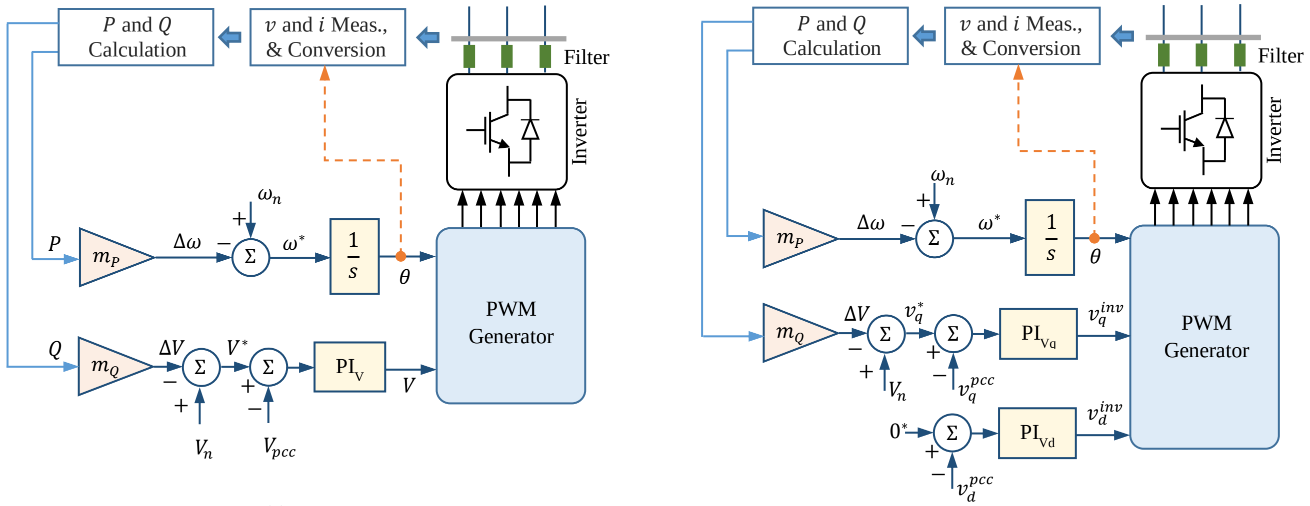
While the former method is simpler, the latter method provides decoupled control of the dq-axis component values of the inverter output voltage. Both methods provide the same voltage amplitude and phase-angle reference. Figs. 2(a) and 2(b) demonstrate the PCC voltage of the grid-forming inverter for the controllers shown in Figs. 1(a) and 1(b), respectively. For both cases, an inverter is operated in grid-forming mode with an initial load of 2 kW and addition of 2 kW load after 0.7 seconds. Fig. 2 shows that the amplitudes of the PCC voltages are regulated to 294.16 V for the two scenarios before and after the load change. However, in Fig. 2(a), for the controller in Fig. 1(a), the d-axis voltage is not regulated to any value, whereas, in Fig. 2(b), for the controller in Fig. 1(b), both q- and d-axis voltages are regulated. It can be inferred from this test that, although the voltage amplitude and the phase-angle of the presented two inverter controllers are equal, controller must be selected based on the application requirement.

IV. Decentralized Power-Sharing

Inverters in a microgrid must share the total power generation in proportion to their capacities. A supervisory control can be utilized for power-sharing, where the control commands are sent to the inverters from a central server through communication channels [36]. However, the supervisory control can be affected by cyberattacks and commination delays that make this type of power-sharing method less reliable [37]. Decentralized power-sharing, on the other hand, does not require any communication channel, and therefore the risk of cyberattack and delay can be eliminated. In this section, some well-known decentralized methods, i.e., droop, and virtual inertia, are reviewed [38], [39].

A. Droop Control for Power-Sharing

Droop control is one of the most used decentralized power-sharing techniques [40]-[44]. In the droop control method, an inverter uses voltage and frequency measurements to identify the power-sharing requirement of a microgrid. Particularly, the frequency can be used as a global parameter for a whole system. In conventional droop control methods, the frequency and the active-power injection by the inverter are linearly related, named frequency-active power droop $(P - f)$. Similarly, the inverter output voltage and the reactive power injection of the inverter are linearly related, named voltage-reactive power $(Q - V)$ droop. The two controllers in Fig. 1 have the conventional droop controls for power-sharing. The inverter measures the active and the reactive power injection, P and Q, and linearly changes the



(a) (b)

Fig. 1. Two most common grid-forming inverter controllers with droop. (a) direct voltage control. (b) voltage control with dq-components

frequency and the voltage references, ω^* and V^*, according to the following equations.

$$\begin{cases}\omega^* = \omega_n - m_P P \\ V^* = V_n - m_Q Q\end{cases} \tag{1}$$

Here, m_P and m_Q are the $(P-f)$ and the $(Q-V)$ droop coefficients. The droop coefficients determine the power-sharing ratios between the inverters in a microgrid. In a microgrid consists of n number of inverters, where P_i is the maximum active power injection capacity and m_{Pi} is the droop coefficient of the i-th inverter, whereas $i = 1,2,3,\dots,n$, the following relationship between the droop coefficients and the capacity of the inverters can be developed from (1) as follows–

$$m_{P1}P_1 = m_{P2}P_2 = \cdots = m_{Pi}P_i \tag{2}$$

Similarly, if Q_i be the maximum reactive power injection capacity and m_{Qi} be droop coefficient, the relationship between the droop coefficients and the reactive power injection capacity of the inverter can be expressed as–

$$m_{Q1}Q_1 = m_{Q2}Q_2 = \cdots = m_{Qi}Q_i \tag{3}$$

It is better to mention that the $(P-f)$ and $(Q-V)$ droops are the most effective in an inductive network, where the R/X ratio is comparatively low. If the R/X ratio is relatively high, i.e., the network is resistive, voltage-active power $(P-V)$ and frequency-reactive power $(Q-f)$ droops are more beneficial [43], [44]. The authors in [45] and [46] developed a method to solve the power-sharing problem at a high R/X ratio with the $(P-f)$ and $(Q-V)$ droops by virtually increasing the effective inductance of the system. In [47], an angle-based droop, $(P-\theta)$, is proposed for active power-sharing between the inverters, where the active-power injection is linearly dependent on the phase-angle. The angle reference, needed by the inverter, is provided by signals from the global positioning system in this method.

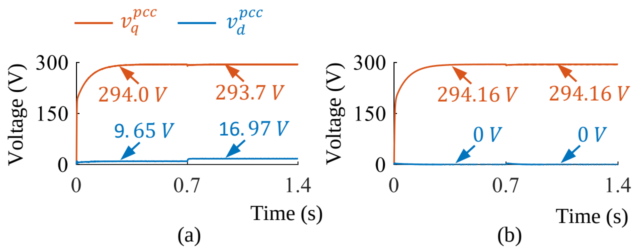
B. Virtual Inertia for Power-Sharing

The droop-based control methods for the inverters are adopted from the droop characteristics of the synchronous generators. However, the inverters, unlike the synchronous generators, are not equipped with inertia and cannot fully utilize the droop characteristics of a system with inertia. This may cause dynamic instability in a microgrid of many grid-forming inverters with droop, in which the under-frequency and the over-frequency relays can be triggered under rapid load changes and disturbances. Therefore, the virtual inertia-based power-sharing methods have been developed to mimic the inherent inertia of the synchronous machine in the grid-forming inverters [39], [48].

Fig. 3 shows a grid-forming inverter controller with virtual inertia. Similar to the swing equation of a synchronous generator, the swing equation of an inverter with virtual inertia can be expressed as follows:

$$P_m - P = J\omega_m \frac{d\omega_m}{dt} + D\left(\frac{\omega_m - \omega}{\omega_n} S_b\right) \tag{4}$$

where, J, D, and S_b denote the virtual inertia, damping factor, and the power rating of the inverter, respectively. The virtual shaft power, P_m, can be obtained from the droop equation, $P_m = (1/m_P)(\omega_m - \omega_n)$, where, ω_m and ω_n are the virtual rotor angular frequency and the nominal angular frequency. The angular frequency of the voltages at the PCC, ω, is a measured parameter that is not always equal to ω_m. The authors in [49] has derived that the droop and the virtual inertia are mathematically similar. In [50], a comprehensive analysis of the dynamic characteristics of the droop control and the virtual synchronous generator is presented, where the grid-forming inverters with the two different types of controllers are modeled for small-signal and electromagnetic transient analysis. The study shows that the rate of change of frequency is higher in the droop control method when a step response is provided.



(a) (b)

Fig. 2. The dq-axis components of the PCC voltage for (a) controller in Fig. 1(a), and (b) controller in Fig. 1(b) at 2 kW and 4 kW injection.

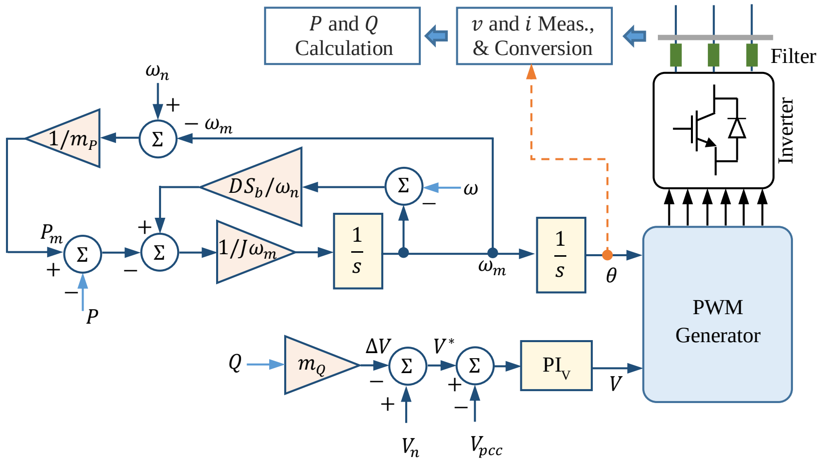


Fig. 3. A grid-forming inverter controller utilizing virtual inertia for power-sharing.

Advanced rule-based adaptive methods have been presented in [51] and [52], where the coefficients are selected based on the preset rules. The virtual inertia-based control can be made adaptive to enhance the stability of the system after a fault by including the inertia constant controllers [53]. In [54], a self-tuning method is presented where both the damping coefficient and the inertia constant are adaptively tuned. The self-tuning method is further improved in [55] by an online optimization method where the frequency deviation is also minimized. Notice that in order to provide the virtual inertia by the grid-forming inverters that properly mimic the rotational kinetic energy reservoir of an electric machine, a well-managed energy storage system is required [56], [57].

V. SYNCHRONIZATION FOR GRID-FORMING INVERTERS

Synchronization is necessary when multiple inverters are operating together in a microgrid. Synchronization for the inverters is conventionally performed by the PLLs, where the inverters are in grid-following mode, and the grid is comparatively stiff [18]. Synchronization between multiple grid-forming inverters is challenging, as the inverters independently controls the voltage and the frequency. Fig. 4 shows a scenario when two grid-forming inverters were connected with improper synchronization. As seen in Fig. 4, the line-line voltage and the active power of the connecting inverter becomes completely unstable, causing the inverters to trip.

Very few works are available on communication-less synchronization for grid-forming inverters. This is because, the microgrid voltage, frequency, and phase angle at PCC are unknown to the synchronizing inverter, while the voltage, frequency, and phase angle vary to accommodate droop-based power-sharing between multiple inverters. Most state-of-the-art synchronization methods allow the inverter to be connected with the grid and operate in grid-following mode [58]. The authors in [59] presented a low bandwidth ethernet communication-based synchronization method where phase-angle and the voltage information are relayed through a separate module known as the synchronization data sender/controller. An FM modulated signal-based synchronization method has been presented in [60]. The synchronization method presented in [61] used synchronverters to synchronize without the dedicated synchronizing unit, where the inverter adjusts with the phase-angle of the grid prior to the synchronization and then gradually synchronizes the frequency like a synchronous machine. In [1], the authors have presented a synchronization method, known as the controller-sync method, where two control paths are run in parallel while only one is engaged at a time. The method automatically synchronizes the controller output without using two separate sets of sensors across the circuit breaker connecting the inverters and the grid.

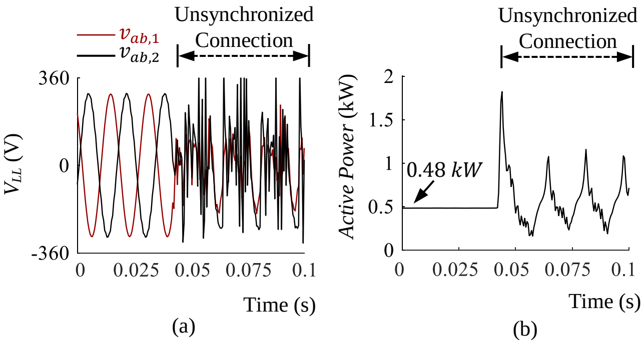


Fig. 4. Condition of (a) line-line voltage, and (b) active power injection by a grid-forming inverter after unsynchronized connection with a second grid-forming inverter.

VI. DECENTRALIZED VOLTAGE AND FREQUENCY RESTORATION

Decentralized power-sharing control of grid-forming inverters inherently causes the bus voltages and the system frequency to deviate from their nominal values for any load change [62]. The frequency and the voltage amplitude at the PCC of the inverter may exceed the permissible operating limit of the distributed energy resources [63] and trip the inverter. Therefore, advanced frequency and voltage restoration methods are needed [64]-[68]. Fig. 5 shows a frequency restoration controller where frequency is restored by the secondary feedback path after any load change or plug-in events.

Notice that keeping the restoration path active all the time does not allow other incoming inverters to share power. Low-bandwidth communication-based control is suggested in [65], where the restoration signal is transmitted through a one-way transmitter from centralized control. The drawback is that any communication delay and distortions, e.g., transmission noise or cyberattack, may disrupt the operation. In [66] and [67], some state-estimation techniques have been introduced to establish a supervisory control on the voltage and frequency restoration. However, the reduction of measurement points and communication networks is traded off with additional computational burdens. There are some timer/counter-based methods where the grid-forming inverters activate secondary feedback/forward paths for the voltage and frequency restoration for a certain period and then deactivate again [68]. In [63], the authors showed that timer-based restoration might cause an error in the restoration if the timer is not properly set or the load is rapidly changed. A threshold-based restoration control method has been presented in [69], where measurement parameters can be used to adaptively change the restoration period. A washout filter-based frequency restoration methods have been presented in [70] where, an adjustable delay inherited

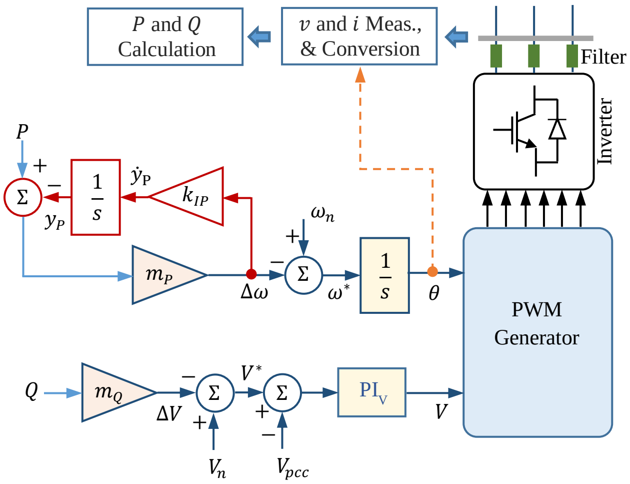


Fig. 5. A grid-forming inverter with droop and secondary control for frequency restoration.

by the low-pass filter is adaptively tuned by the variation of the active and reactive power injection.

VII. CONCLUSIONS

Several control methods for the grid-forming inverters for power-sharing, synchronization, and voltage and frequency restoration have been briefly discussed in this article. Two most basic grid-forming control strategies have been presented. It has been shown that, although the output voltage amplitude and frequency obtained from the two basic controllers are the same, the q and d-axis components can be different. Droop and virtual inertia based power-sharing methods have been reviewed. While the droop-based methods are straightforward and easy to implement, virtual inertia-based methods can be used to artificially include inertia in an inertia-less system. Two grid-forming inverter synchronization methods have been reviewed in this article. The article has also reviewed the state-of-the-art frequency and voltage restoration methods developed for decentralized operations that focus on the local measurements for more accurate performances. All these control features, when combined, can intensify the role of an ordinary grid-forming inverter as the next-generation power source for the future power grid.

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