Overview of Power Converter Control in Microgrids—Challenges, Advances, and Future Trends

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***Abstract*—As the electronic interfaces between distributed energy resources and the electrical network, power converters play a vital role in voltage stabilization and power conversion. So far, various power converter control methods have been developed. Now it is urgently needed to compare and understand these approaches to support the smart microgrid pyramid. This article provides an overview of the state-of-the-art of parallel power converter control in microgrid applications. The most important control schemes to address existing challenges, including concentrated control, master–slave control, droop mechanism, virtual synchronous generators, virtual oscillator control, distributed cooperative control, and model predictive control, are highlighted and analyzed in detail. In addition, the hierarchical control structure, as well as future trends, are reviewed and discussed.**

***Index Terms*—Microgrids, power converter control, renewable energy.**

I. INTRODUCTION

MICROGRIDS, as the key building blocks of the smart grid, are clusters of local loads and distributed generations (DGs) such as wind turbines (WTs), solar photovoltaic (PVs), and energy storage systems (ESSs). They can offer distinct advantages over traditional power grids in such a way that distributed renewable and nonrenewable energy sources can be flexibly integrated into the power network [1]. In DG integration, either connected to the distribution network or a local load, the key components during this power conversion process are power electronic converters, which provide flexible interfaces between the power sources and the end users [2]. In microgrids, three important tasks include the following:

1) load sharing among multiple DGs proportionately;
2) voltage and frequency stabilization;
3) power flow optimization.

With the increasing penetration of DGs, high-performance power converter control strategies are highly desired to achieve these goals.

Research on the control of power converters in microgrids stems initially from uninterruptible power supply systems with parallel inverters [3]. Since then, there has been ongoing research on advanced control strategies to achieve better dynamic response and steady-state performance. Control strategies of DGs relying on communication include concentrated control [4]–[6], master–slave control [7]–[9], and distributed control [10], [11]. By contrast, in decentralized control strategies, such as the droop mechanism, communication among DGs can be avoided [12]–[19]. Most of the control methods ever developed, particularly in the last few years, are based on the droop concept. The basic idea is to emulate the behavior of synchronous generators in which the frequency is reduced as the active power demand increases. Since then, many improvements have been made to enhance system performance. For example, virtual output impedance is proposed for various purposes such as active and reactive power decoupling under complex line impedance [15] and harmonic power sharing under nonlinear loads [16]. To improve the transient response, power derivative-integral terms are introduced into conventional droop schemes [17]. To mitigate the frequency and voltage deviations, angle droop and virtual flux droop approaches are proposed [18], [19].

Actually, in addition to droop methods, there are alternatives, which are usually ignored by researchers. These alternatives present distinct advantages and potentials in microgrids. In a power electronics-rich power grid with more and more inertial distributed energy resources (DERs), traditional droop control schemes cannot provide sufficient inertia, hence resulting in a rapid rate of change of frequency (ROCOF) under disturbances. To address the inertia problems in droop control, the virtual synchronous generator (VSG) concept is proposed [20]–[24].

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Recently, virtual oscillator control (VOC) emerges as a promising power converter control method [25]–[30]. It is a scheme that digitally emulates a nonlinear oscillator circuit with the inverter output current as an input and the oscillator dynamic states are used as the modulation signal to generate PWM switching signals for inverters. Since it does not require voltage measurement and power calculation with low-pass filters, a fast response during transients can be obtained.

Meanwhile, other advanced control strategies have been developed for further improvement. For instance, distributed cooperative algorithms have been applied in microgrids to achieve the functionalities of both primary and secondary controls without relying on droop strategies [31]–[33]. Each DG is treated as an agent of a multiagent system (MAS). Through exchanging information with a few of their neighbors, individual inverters update their local voltage set points and synchronize their frequencies based on consensus algorithms. Model predictive control (MPC), which uses system present status and available control actions to predict future system behaviors, is another promising converter control approach in microgrids. One of the research streams aims to remove the inner cascaded voltage and current loops by introducing finite control set MPC (FCS-MPC) controllers while the outer droop characteristics are retained [34]–[37]. The main merit of using MPC is a faster dynamic response in power regulations and voltage stabilization. Another research stream focuses on the multiple-input-multiple-output (MIMO) state-space model to express the parallel-connected inverters system [38]. Based on this model, continuous control set MPC (CCS-MPC) is adopted to achieve load sharing and circulating current elimination among inverters without using a droop mechanism.

To date, as many control methods have been developed and applied, it is urgently needed to provide an overview to better compare and understand these approaches. Indeed, some reviews have been presented in the literature, addressing the challenges and control in microgrids. For instance, in [39] and [40], the authors extensively discuss power-sharing methods for parallel inverter-based microgrids. The drawbacks of the droop mechanism, including frequency and voltage deviations, active and reactive power coupling, harmonics, and communication delay, have been identified. Corresponding techniques to address these drawbacks are reviewed. Sahoo *et al.* [41] provide a comprehensive review of droop-based decentralized control at the primary layer for power sharing as well as the secondary layer for voltage and frequency restoration. The work presented in [42] provides an overview of microgrid structures and control techniques from the perspective of three inverter operation modes, i.e., grid-forming, grid-feeding, and grid-supporting configurations. Nevertheless, none of these works mentioned above consider other advanced and promising control techniques in addition to the droop concept. Overviews of distributed control have been presented in [11] and [43], where the benefits of the distributed control, MAS, in particular, are highlighted. However, they do not cover important topics such as conventional centralized control and recent advancements. A comprehensive review of microgrid control for both power-converter level and system level is presented in [44], but only the MPC algorithm is studied. Vasudevan *et al.* [45] provide an overview of various virtual inertia emulation techniques, with a focus on a synchronverter and its recent development such as augmented control loops, self-synchronization, and modified single-phase synchronverters. In addition, parameter tuning methods and stability assessment of synchronverters are discussed.

More recently, some reviews of microgrid control have been reported. In [46], an overview of control and management techniques for microgrids is carried out. The requirements and control objectives of different hierarchical control layers have been reviewed. Unfortunately, it lacks an in-depth insight into power converter control and operation at the device level. Similarly, the work in [47] provides a review of power converter control strategies and their applications to ac and dc microgrids. However, the practical challenges in power converter control in the microgrid are not revealed, and important research streams such as VOC and VSG are not covered. The work in [48] presents a comprehensive review of different types of interconnected electric power networks, including high-voltage direct current interconnection, synchronous ac interconnection (interconnected networks having the same frequency and voltage level), and asynchronous ac interconnections (interconnected networks having different frequencies and voltages). Then, various power flow controllers, either constructed using power electronic devices, electromechanical devices, or the combination of these two, are discussed. The work is focused on large power systems, whereas power converter control for microgrids is not detailed.

In this article, an overview of power converter control at a primary control layer (i.e., device level) in microgrids is presented. In addition to the droop mechanism that has been widely studied over the past years, other important and promising control approaches, including concentrated control, master–slave control, VSG, VOC, droop-free distributed cooperative control as well as MPC, are highlighted and analyzed in detail. The rest of this article is organized as follows. The microgrid hierarchical control framework is described in Section II. The key challenges in power converter control in microgrids are identified in Section III. The most important and popular control techniques are reviewed in Section IV. The future trend is discussed in Section V. Finally, Section VI concludes this article.

II. HIERARCHICAL CONTROL ARCHITECTURE

It is emphasized that the power converter control strategies at the primary control layer are focused and reviewed in this article. Yet, it is necessary to briefly discuss the hierarchical control architecture, as presented in Fig. 1. Conventionally, hierarchical control, or multilayer control, is a common and effective way to govern a complex system such as a power system. It has now been applied in microgrids and is widely recognized as a standard control architecture. Under a hierarchical control framework, different control objectives are associated with various control layers. These three levels are differentiated by specified control objectives and bandwidths.

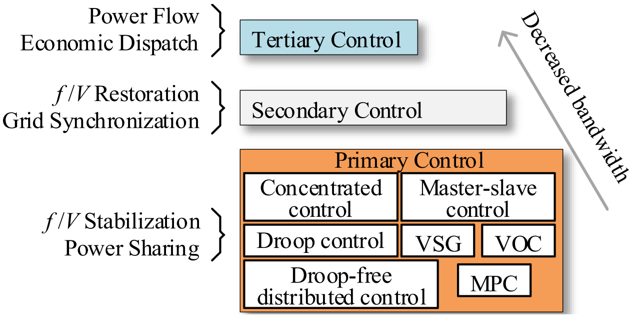


Fig. 1. Hierarchical control architecture for microgrids.

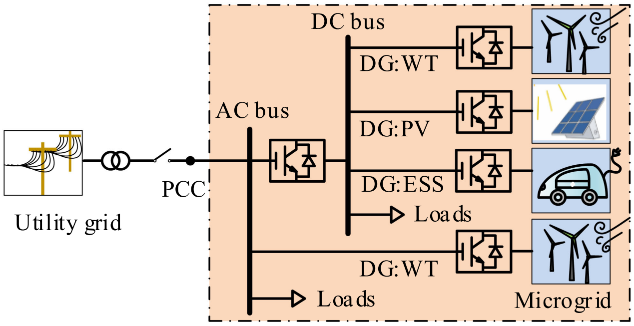


Fig. 2 Microgrid configuration integrated with DERs.

A. Primary Control

As the name suggests, it is the underlying level that stabilizes the whole system in terms of voltage and frequency within the acceptable ranges while enables load sharing among DGs with fast response. As will be extensively discussed in Section IV, control strategies such as concentrated and master–slave approaches, droop mechanism, droop-free distributed cooperative control, VOC, and MPC, can be used in the primary control level. In practice, for the sake of cost reduction and high reliability, it is preferable to apply control methods that do not rely heavily on communication links, particularly in remote areas such as regional towns and islands. A system without centralized communication infrastructure is easier to expand as it allows adding/removing DGs without having to shut down the whole system.

B. Secondary Control

By using primary control strategies such as droop methods, the power balance under load changes is maintained by adjusting system voltage magnitudes and frequencies. Unfortunately, this mechanism inevitably results in voltage deviations from nominal values. To eliminate these deviations, secondary control is utilized to update the set points of the local primary controls according to the following equation [49]:

$$\begin{aligned} \delta\omega &= H_{p\omega}\left(\omega^* - \omega\right) + H_{i\omega}\int\left(\omega^* - \omega\right)dt \\ \delta E &= H_{pE}\left(E^* - E\right) + H_{iE}\int\left(E^* - E\right)dt \end{aligned} \tag{1}$$

where $H_{p\omega}$, $H_{i\omega}$, H_{pE}, and H_{iE} are the compensators of the closed-loop transfer functions. ω and E are the angular frequency and amplitude of the DG output voltage, respectively. Superscript $*$ denotes the reference quantity. To increase the system reliability and expandability, distributed secondary control methods have gained significant attention [49]. Here, it is worth mentioning that secondary is not necessarily compulsory, depending on the primary control performance.

C. Tertiary Control

As the highest layer in the hierarchy, tertiary control acts as a supervisory management system for monitoring and coordination. It deals with operation scheduling and economic dispatching. Advanced optimization algorithms are usually executed in this layer to generate optimal power setpoints. These power setpoints will then be sent to lower control layers for controlling power converters. As the foundation of tertiary control, reliable power flow analysis is critically important to explore the potential of microgrids as resilience resources. Based on this, power flow should be optimized, with respect to grid requirements and element constraints, to reduce energy cost, avoid undesired power loss and reduce peak grid power supply. Notice that tertiary control is also applicable for networked microgrids in which multiple microgrids interact with one another for power exchange and voltage support [50].

III. KEY CHALLENGES IN POWER CONVERTER CONTROL IN MICROGRIDS

With the rapid growth in DERs such as solar PVs, WTs, wave generators, and electric vehicles (EVs), more and more power electronic converters are being utilized to connect the power sources to common ac and/or dc buses in microgrids, as illustrated in Fig. 2. In order to ensure a stable and proper operation, several challenges must be addressed.

A. Load Sharing

In practice, the capacities of various DGs are different, depending on the actual power outputs from renewable energy. The converter interfaced DGs in a microgrid should pick up the load changes according to the inverter capacity as well as the actual power outputs from DGs in order to avoid overload or power deficiency under variable power generation and consumption conditions. In other words, the load demand should be shared among parallel converters accordingly. Otherwise, overload could occur, leading to overcurrent or even voltage collapse.

B. Power Quality

One of the major tasks in converter control is to stabilize the system voltage and frequency within microgrids. It is noted that power electronic converters themselves are the major sources of harmonics that pollute the power grid due to high-frequency switching operations. Nevertheless, if controlled properly, they can be used to address power quality problems such as voltage harmonics, spikes, and unbalances [51]. Also, nonlinear loads and unbalanced grid conditions have posed significant challenges for voltage/frequency stabilization and total harmonic distortion minimization. In this sense, the controller should deal with power sharing for the fundamental components as well as harmonics in presence of nonlinear loads.

C. Circulating Current

In practice, circulating current could be generated among parallel inverters due to the differences in output voltages and dc offsets of output currents, which are essentially caused by the differences in system and control parameters such as switching frequencies, line impedances, drifts of hardware components, etc. Particularly, zero-sequence circulating currents have become major concerns [50]. Such circulating currents may lead to output voltage distortion and different current stress on switching devices, resulting in additional power losses and lower reliability.

D. Mismatch and Unknown Line Impedances

As discussed previously, if the impedances of the power lines between DGs and point of common coupling are not the same, it could lead to circulating currents. Actually, the mismatch in line impedances can further result in inaccurate power sharing among distributed inverters. Another issue is the effect of the power line *R*/*X* ratio. For example, the conventional *Q*–*V* and *P*–*f* droop method is derived based on the assumption of highly inductive equivalent impedances between inverters and the common bus. Nonetheless, this assumption is not valid in low-voltage (LV) microgrids where distribution power lines are predominately resistive. Moreover, in medium-voltage microgrids where the line impedance is a complex form with both resistive and inductive terms, the active and reactive powers are strongly coupled. Usually, the *R*/*X* ratio of the power line is unknown and difficult to obtain. This brings in significant challenges in designing a proper control strategy for accurate power sharing.

E. Renewable Energy Intermittency

The intermittency of renewable energy resources and fluctuating load profile can lead to the power unbalance of a microgrid. In this case, some DGs may have surplus energy while others may experience power deficiency. If the power generation cannot be coordinated properly, e.g., DGs with power deficiency are still controlled to supply power according to their rated capacity, frequency divergence or voltage collapse may occur. With stochastic power output from renewable energy sources, adaptive control strategies should be employed to achieve accurate load sharing. Control parameters such as the droop gains, embedded in the controller, should be adjusted to achieve adaptive load sharing according to actual situations of each stochastic source.

F. Cyber-Physical Network

From the power flow viewpoint, a microgrid is an electric network that forms physical power connections between power sources and loads. So far, several configurations have been developed [53]. No matter which configuration is adopted, such a physical system should be associated with a cyber network to fulfill communication requirements and exploit different control opportunities. In this sense, a microgrid is essentially a cyber-physical system in which the communication network enables data exchange among DGs for monitoring and control purposes. In most of the literature, it is usually assumed that data and signals are transferred to and from the control center or among DGs over an ideal communication network. However, data dropouts, time delays, transmission intervals, or even failures can occur in a real communication network [33]. Such practical issues can deteriorate converter control performance. It is noted that the topology of the cyber network is not necessarily identical to that of the physical power network. But one thing is certain is that the communication structure should be optimized with the consideration of physical electric network as well as control parameters. Also, it should be endowed with a high degree of flexibility to accommodate the scalability of microgrids with plug-and-play capability.

IV. CONTROL SCHEMES OF POWER CONVERTERS IN MICROGRIDS

To address the challenges discussed above, appropriate control strategies are needed. For better illustration, the most important and popular control methods are summarized and compared in Table I before we dig into each technique.

A. Concentrated Control

Concentrated control, which is also known as centralized control, is depicted in Fig. 3(a). There are two-layer control loops, namely an overall voltage control loop on top and local current control loops for individual converters. The actual load voltage is measured and compared with the reference. The error is then sent to the voltage controller. The output current reference from each inverter is identical, which is obtained by averaging the total load current. Therefore, it is essentially a current averaging method [4]. The current reference value is then compared with the actual current of each module or inverter. The errors are sent to inner current control loops with PID/PR regulators. Eventually, the voltage controller output will be added up to the current controller output to form the voltage reference for individual inverters. Subsequently, PWM modulators are employed to produce switching signals [5], [6], [54]. Using this method, current measurement at each module and then the calculation of the total load current is required. Hence, this control method is impractical in a large microgrid with many DGs due to the significant communication and computational burden.

B. Master–Slave Control

In this method, as depicted in Fig. 3(b), one inverter operates as the master module to supply a stable sinusoidal ac voltage for the loads. It also determines the current references for the rest of the modules [7]. The remaining modules receive the current reference from the master module for current sharing [8], [9]. The distributed reference current is determined in the power distribution center according to the rated capacity of each

TABLE I
COMPARISON OF CONTROL TECHNIQUES FOR COORDINATION OF PARALLEL POWER CONVERTERS

Major techniques	**Features**	**Advantages**	**Disadvantages**	**Applicability**
Concentrated control [4]-[6], [54]	Centralized controller	Accurate load sharing in steady state and transients	Low reliability and expandability	High bandwidth communication requirement
Master-slave control [7]-[9], [55]-[57]	Slave units communicate with the master unit. Master and slave role can be swapped.	Accurate current sharing in steady state	Current overshoot during transients	Suitable for networks with different types of DGs.
Droop control [12]-[19], [58]-[60]	Decentralized control, P, Q sharing according to pre-defined droop characteristics	No communication links, high reliability	Slow response, inaccurate power sharing under complex line impedances	Suitable for networks with similar DG types and less communication facilities
VSG [20]-[24], [63]-[65]	Modified droop control with virtual inertia	Enhanced frequency stability	Pre-existing knowledge on the network operation, real-time frequency measurements	Useful for networks with high penetration of power electronics-based DERs. Provide virtual inertial support.
VOC [25]-[30], [66]	Emulate the dynamic characteristics of limit-cycle oscillators; time-domain controller	Fast response during transient without power calculation, less frequency deviations	Lack of compatible grid synchronization techniques, third harmonic at the output voltage	Networks with linear and nonlinear loads. No communication is required.
Droop-free distributed control [31]-[33], [68]	Sparse communication network without central controller	Improved reliability, effective voltage regulation and frequency synchronization, accurate load sharing for complex line impedances.	Vulnerable to communication delay	Reduced bandwidth communication requirement; Microgrids with spatially dispersed DGs
MPC [34]-[38], [81]-[83]	Select the best control action based on a cost function and the prediction model	Fast transient response in power regulation and voltage stabilization	System model dependent; large computational burden	Circulating current mitigation; Suitable for microgrids with various control objectives and constraints

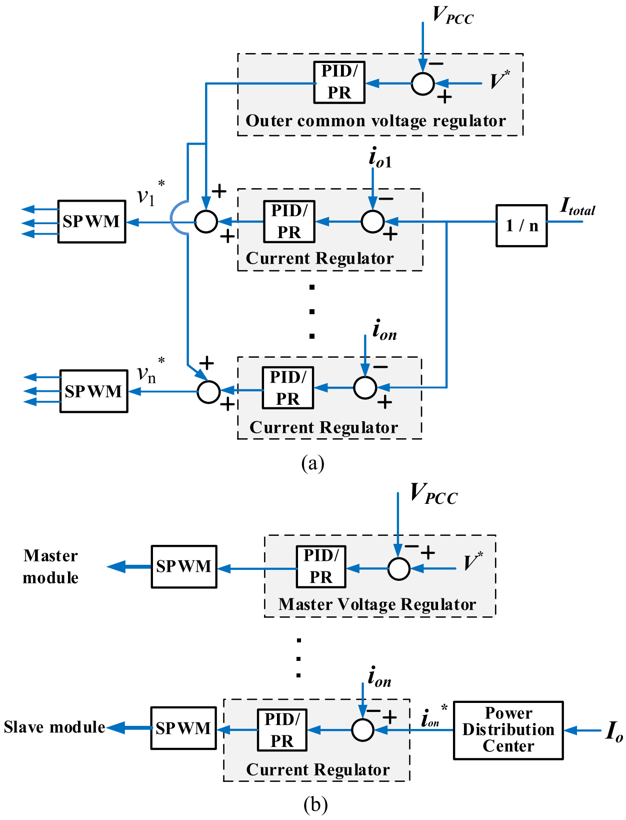


Fig. 3 Centralized control. (a) Concentrated control. (b) Master–slave control.

module including the master and slave units as [7]

$$I_{oi}^* = I_o \times \frac{S_i \times W_i}{\sum_{i=1}^{n} (S_i \times W_i)} \tag{2}$$

where I_o is the total load current; S_i is the rated capacity of the ith module; W_i is either 1 or 0, representing the ON/OFF status of the ith module. In this way, the load can be shared properly among parallel inverters, and PLL circuits are not needed to synchronize the parallel operation. To mitigate the impacts of voltage disturbance and improve current sharing response, a voltage feed-forward loop and a current feed-forward loop can be included in the current controller for each slave module. Consequently, the load current can be shared accurately according to the commands delivered from the control center. In this configuration, to avoid an overall failure of the system, one of the slave modules will take over the master role if the original master inverter fails.

In fact, the master–slave concept can be extended by incorporating other control methods and considering various constraints. For instance, [55] presented a sliding mode control (SMC) based primary control strategy of a master–slave organized microgrid. Specifically, the voltage-mode SMC is implemented in a master DER unit, while the current-mode SMC is embedded in the slave units. The developed control strategy enables fast and stable voltage and frequency regulation, even under unbalanced and/or distorted load current conditions. In master–slave control, overshoot currents may occur during transients since the output currents of the master units are not controlled directly. To overcome this drawback, one simple solution is to introduce an inner current loop in the master controller to limit the current overshoot, though this brings in additional control complexity to the system. Further, one more step can be taken to change the parallel architecture to a series-cascaded connection for inverters [56]. In this way, all DGs, including the master unit and slave units, carry the same current. Thus, overshoot currents can be shared and mitigated among DGs. Another typical example can be found in

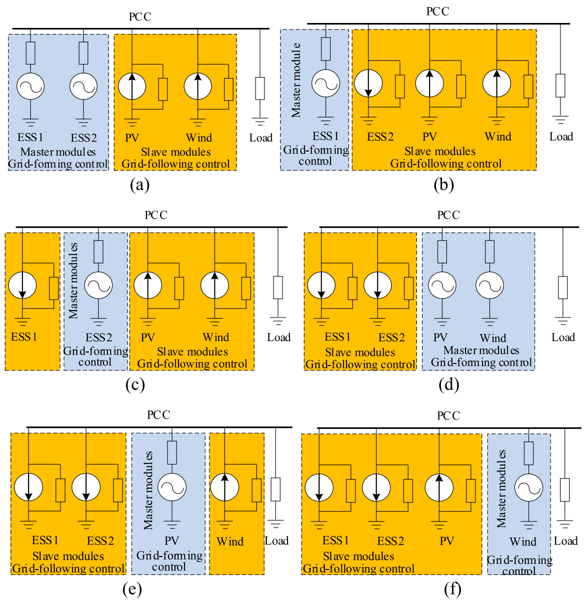


Fig. 4 Coordination strategy for a microgrid with renewable generation and storage: Blue color indicates master modules; orange color indicates slave modules. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5. (f) Mode 6.

[57] where a distributed master–slave architecture is presented. The renewable energy sources (RES) and ESS can operate in either grid-forming control as master modules or grid-following control as slave modules, depending on actual conditions. The following three basic rules are applied to determine the operation modes.

1) At least one DER has to serve as a master module with grid-forming control to stabilize common bus voltage.
2) The master and slave role should be swapped between ESSs and RESs based on their real-time capacities, constraints, and operating conditions.
3) RESs should have a high priority to operate in grid-following control to generate maximum power from available wind and solar energy unless the ESSs are not able to perform a grid-forming operation.

For better illustration, Fig. 4 depicts six possible operation modes in the coordination architecture. At mode 1, all the ESSs regulate the common bus voltage by using grid-forming approaches such as the droop method, while the RESs generate maximum power with MPPT techniques by regulating output currents. The ESSs can be charged or discharged, depending on the power unbalance between generation and demand. In Modes 2 and 3, one of the ESSs has changed to a slave module with grid-following control to absorb energy due to a low capacity. In Modes 4, all ESSs are under grid-following control to store energy, while all RESs serve as master modules with grid-forming control to share the power demand. In Modes 5 and 6, when the maximum available power from one of the RESs drops below the level that should be shared with the other RES, it returns to grid-following control. In this case, only one RES serves as the master module, until it does not have sufficient power. At this point in time, the microgrid can either return to Mode 1, perform load shedding, or completely shut down.

C. Droop Control

For the coordination of multiple converters in a microgrid, preferably, the control approaches applied should be independent of communication links. This is because the DGs could be located far away from each other, which causes additional system costs and degrades system reliability with long communication lines. Different from the active load sharing techniques discussed previously, the droop concept mimics the characteristic of a synchronous generator in a power system, in which frequency is decreased when the load consumption increases. The active and reactive power flows between DGs and the common voltage bus can be expressed as [15]

$$P = \frac{EV\cos(\theta-\phi)}{Z} - \frac{V^2}{Z}\cos\theta \tag{3}$$

$$Q = \frac{EV\sin(\theta-\phi)}{Z} - \frac{V^2}{Z}\sin\theta \tag{4}$$

where E and V are the inverter output voltage and the common bus voltage, respectively; ϕ the power angle, i.e., the phase of the DG output voltage; Z and θ the magnitude and the phase of the output impedance, respectively. For a mainly inductive output impedance, (3) and (4) can be further simplified into

$$P = \frac{EV\sin\phi}{X} \tag{5}$$

$$Q = \frac{EV\cos\phi - V^2}{X}. \tag{6}$$

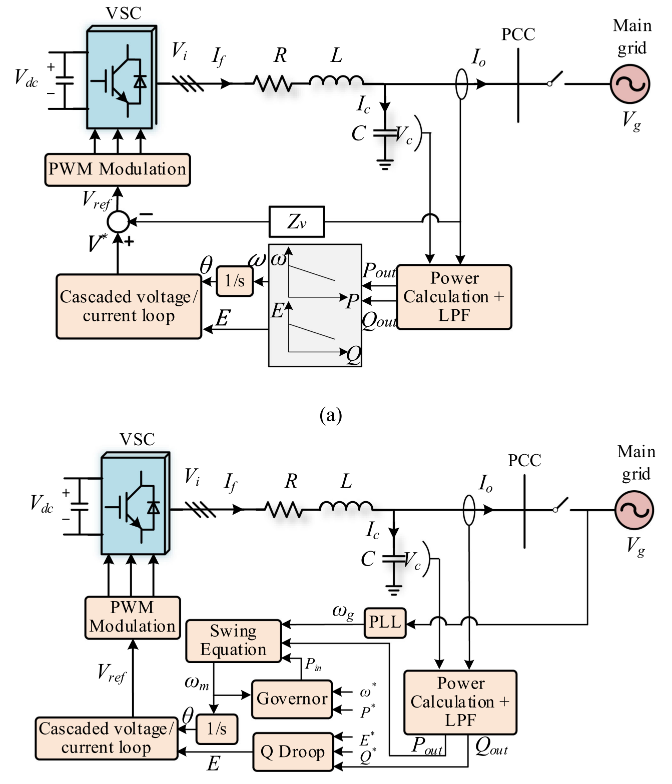
It can be seen that P is predominantly dependent on the power angle ϕ while Q is mainly influenced by the amplitude difference (E-V). Consequently, artificial P-ω and Q-V droop characteristics can be introduced as

$$\omega = \omega^* - m(P_{\text{out}} - P^*) \tag{7}$$

$$E = E^* - n(Q_{out} - Q^*) \tag{8}$$

where m and n are the droop gains, ω^* and E^* the voltage angular frequency and amplitude references, P_{out} and Q_{out} the actual active power and reactive power outputs, and P^* and Q^* the reference active power and reactive power, respectively. By using this approach, the active and reactive powers from individual inverters are manipulated according to a pre-define droop manner by adjusting their output voltage frequency and amplitude, respectively.

Fig. 5(a) presents the structure of the droop control method, which consists of the outer power droop and an inner cascaded voltage/current regulation loop. In outer the droop controller, the P and Q are calculated based on the measurement of inverter output voltages and output currents, and then averaged through low-pass filters. The calculated powers together with the nominal power references $P^*$and Q^* are delivered to a predefined droop curve to generate the voltage reference E^*. After that, the voltage reference will be used for the inner voltage/current control loop. The inner voltage/current control loop usually



(a)

(b)

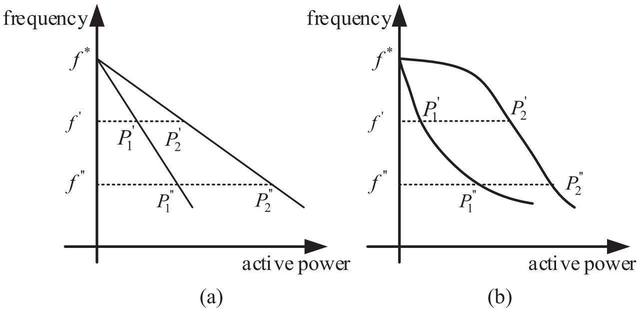
Fig. 5 Droop-based methods. (a) Droop control. (b) VSG.

includes two cascaded control loops, i.e., voltage tracking and current regulation.

Over the past years, there have been many improved methods proposed to enhance droop performance. For instance, in a low voltage distribution network under resistive feeder impedance conditions, *P-Q-V* droop schemes can be used to achieve equivalent active power sharing [12]. To address inaccurate *P* or *Q* sharing and slow transient response problems under complex line impedances, several solutions have been proposed, including virtual frame transformation methods [14] and virtual impedances [15], etc. In the virtual impedance method, the inverter output voltage reference is reduced proportionally to the output current as

$$V_{ref} = V^* - Z_v I_o \tag{9}$$

where Z_v is the virtual output impedance. For either mainly inductive or restive distribution lines, by adjusting the virtual impedance properly, active and reactive powers can be decoupled. It is noted that virtual impedances can also be adopted to realize harmonic power sharing in the presence of nonlinear loads for power quality improvement [16]. To reduce the frequency deviation, some researchers have proposed the angle droop and virtual flux droop strategies [18], [19]. Instead of drooping the frequency, the power angle or the virtual flux of the inverter is adjusted. The angle droop can also provide proper load sharing among DGs while mitigating the frequency deviation at steady states. The main challenge is the synchronization of power angles among DGs. To deal with actual fluctuating power output from renewable energy, an adaptive droop scheme with an enhanced virtual impedance is developed in [13]. Unlike traditional droop control approaches where the droop gains are kept constant by assuming that DGs can always have sufficient power for the loads, the droop gains in this article are changed dynamically with respect to actual power outputs from solar panels to avoid power deficiency, in particular, DGs as



(a) (b)

Fig. 6 (a) Conventional linear droop. (b) Nonlinear droop.

$$m = {}^{\Delta\omega}/_{S_a}, n = {}^{\Delta V}/_{S_a} \tag{10}$$

where S_a is the available power capacity. By using adaptive droop coefficients, proper power sharing among DGs can be achieved even DGs' capacities vary.

Another practical problem is the different types of DGs. Thus, in addition to DG power ratings in droop design, other aspects such as DG operating cost, efficiency, and emission penalty should be considered since they contribute to the total operational cost of the entire microgrid. For instance, for a DG using a diesel generator, the fuel consumption cost rises with the increase of power generation following a quadratic function. In this case, from the operating cost perspective, it is more appropriate to share its power output nonlinearly rather than linearly. To address this problem, nonlinear droop relations were proposed [58], [59]. Fig. 6 compares the conventional linear droop and nonlinear droop. Taking the *f-P* droop, for example, it can be seen that the active power is shared among DGs linearly with a constant droop coefficient for each DG that is determined according to the allowable voltage deviation and the power rating. By contrast, the *f–P* relation is constructed in a nonlinear manner as

$$f = f^* - F_{drp,i}(P_i) \tag{11}$$

where $F_{drp,i}(P_i)$ is an arbitrary nonlinear function that has to be designed properly to achieve different optimization objectives. In [60] and [61], an improved nonlinear droop relation is constructed as a combination of integer and fractional power functions whose parameters are selected using a two-stage particle swarm optimization algorithm. The simulation and experimental results show that, compared with conventional linear droop, the proposed nonlinear droop relation leads to the reduced operating cost of the source and more effective reactive power sharing. Later on, nonlinear droop has also been applied to dc power systems. For example, Chen *et al.* [62] presented a generic polynomial expression to unify different droop equations for dc power distribution systems. The selection and design guidelines of nonlinear droop are also summarized, considering both static performance and interaction with load systems.

D. Virtual Synchronous Generators

In conventional power systems, synchronous generators are able to stabilize the frequency throughout the power network because of the kinetic energy reservoir in the rotating mass. However, with the increasing penetration of DERs with less inertia, the frequency of the microgrid may fluctuate too fast to be maintained under load disturbance (e.g., starting or disconnection of high-power induction motors), leading to a rapid ROCOF. Due to the stochastic nature of RESs and load profiles, most of the modern microgrids suffer from dynamic frequency stability issues, which in turn limits the penetration level of DERs to microgrids.

Even though DGs with droop control can share the power demand, they do not have inertial support to the power system. To cope with the inertia problem, one of the effective inertial emulation techniques is the VSG, which is proposed to provide additional inertial support from DGs with static power electronic converters [20]–[22]. In general, VSG techniques can be classified into current-controlled VSG and voltage-controlled VSG [63]. Recently, voltage-controlled VSG approaches show increasing applications in microgrids as they have grid-forming ability for islanded operation. Fig. 5(b) depicts the control structure of VSG. The "Governor" in VSG can be expressed as

$$P_{\text{in}} = P^* - k_p\left(\omega_m - \omega^*\right) \tag{12}$$

where P_{in} is the virtual shaft power determined by the governor. P^* is the reference active power. k_p is the droop coefficient. ω_m represents the virtual rotor angular frequency, and ω_0 represents the nominal angular frequency, i.e., reference angular frequency. To emulate the rotor inertia of a synchronous generator, the swing equation can be integrated into VSG as

$$P_{\text{in}} - P_{\text{out}} = J\omega_m \frac{d\omega_m}{dt} + D\left(\omega_m - \omega_g\right) \tag{13}$$

where P_{out} denotes the measured output power. J and D are the virtual inertia and damping factor, respectively. ω_{g} is the grid angular frequency. Substituting (12) into (13), one can obtain [64]

$$P^* - k_p\left(\omega_m - \omega^*\right) - P_{\text{out}} = J\omega_m \frac{d\omega_m}{dt} + D\left(\omega_m - \omega_g\right). \tag{14}$$

Let $J = 0$ and $D = 0$, the above equation can be simplified as

$$\omega_m = \omega^* + \frac{P^* - P_{\text{out}}}{k_p}. \tag{15}$$

It can be observed that (15) is equivalent to (7) with $k_p = 1/m$. This in-depth investigation reveals that conventional droop control is actually a special case of VSG. In this sense, in microgrids with parallel inverters, VSG is essentially a modified droop control structure with a first-order lead-lag unit.

Fig. 7 depicts the actual implementation of VSG. Notice that ω_g can be replaced by the nominal frequency $\omega*$ to avoid the use of PLL to detect grid frequency. By using VSG, it has been demonstrated that slower ROCOF can be achieved with a larger virtual inertial J during system disturbance such as sudden load change [64]. To date, various research efforts have been paid to incorporate the VSG method into power converter control to maintain the power balance and enhance system stability. For example, in [65], VSG is applied in the LV network by incorporating virtual impedance to make the total line impedance inductive. In [23], an adaptive virtual inertia method is developed to enhance the dynamic frequency regulation of a microgrid. This adaptive and flexible scheme can offer either large inertia support or small inertia support, depending on actual needs. Specifically, a relatively large inertia is implemented to limit the ROCOF if the frequency deviates from the rated value once external disturbance occurs. Then, a relatively small inertia is emulated to enable faster system dynamics when the frequency starts to return to the nominal frequency. Another practical issue in VSG control is the intermittency and fluctuation of renewable energy. Because of this, changing only the inertia and damping coefficients may be not sufficient to regulate the system frequency. To address this, an MPC-VSG is proposed to simultaneously improve the dynamic characteristics of system frequency and voltage [24].

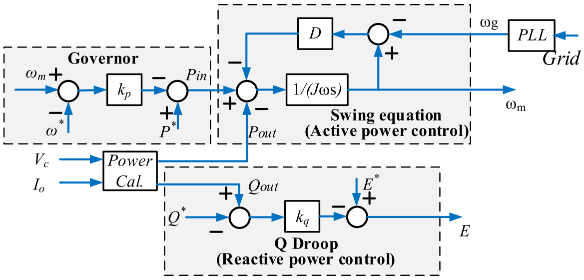


Fig. 7 Detailed block diagram of VSG.

E. Virtual Oscillator Control

VOC is an emerging control approach that emulates the dynamic feature of limit-cycle oscillators [25]–[30]. It has been applied to a single-phase microgrid [25] and a three-phase microgrid [28]. The development of VOC is inspired by the Van der Pol oscillator, which consists of a passive *RLC* circuit as well as a voltage-dependent current source with a dead-zone function. Mathematically, the oscillator dynamics can be described by the following nonlinear differential equations [25]:

$$\begin{cases} \frac{dv}{dt} = \frac{1}{C}\left(\sigma - \frac{1}{R}\right)v - f(v) - i_L - i \\ \frac{di_L}{dt} = \frac{v}{L} \end{cases} \tag{16}$$

where R, L, and C are the resistance, inductance, and capacitance of the passive *RLC* circuit, respectively. v denotes the voltage across the *RLC* circuit. i_L and i are the inductor current and the total current of the oscillator, respectively. $f(v)$ is a dead-zone function with slope 2σ. Intuitively, the electrical energy exchanges between the passive the *RLC* circuit and the voltage-dependent current source periodically at the resonant frequency. The DG output current acts as an input to ignite the oscillator and then the voltage across the *RLC* circuit is used as the modulation signal to control the inverter. Fig. 8 illustrates the

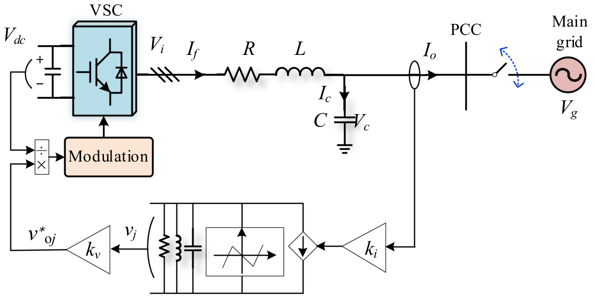


Fig. 8 Block diagram of VOC for parallel inverters.

implementation of VOC. The DG output current I_o is measured and then scaled by factor k_i before being sent to the oscillator. The periodical voltage of the *RLC* circuit as the output of the oscillator v_j is multiplied by a coefficient k_v to produce an ac voltage reference, denoted $v^*{}_{oj}$. After normalized with respect to the inverter dc-link voltage, this voltage modulation signal is compared with the carrier to produce switching signals.

In contrast to droop approaches, VOC is a time-domain oscillator that uses instantaneous current as "excitation" without power calculations/averaging or explicit frequency/voltage references. It features a faster response during transients. More importantly, the system frequency experiences less deviations under load variations, and the supplied voltage can be regulated within prescribed bounds without communication. Despite the advantages mentioned above, VOC has two limitations, i.e., lack of compatible grid synchronization technologies and the existence of the third harmonic contained in the oscillator output voltage. Recently, research efforts have been paid to address these shortcomings. For instance, in [29], an improved VOC is developed for grid-connected inverters to suppress the third-order harmonic in the inverter output voltage. Also, compared with conventional VOC with notch filters, the grid-synchronization response can be improved. To facilitate the utilization of VOC in microgrids, Awal *et al.* [30] present a compatible hierarchical control method for VOC of parallel inverters. By using this approach, the fast dynamic response can be retained while achieving a seamless transition between islanded and grid-connected modes.

More recently, a dispatchable control for virtual oscillator controlled inverters is presented to achieve simultaneous regulation of both the active and reactive power in a single-phase microgrid [66]. The embedded Q–ω and P–V droop characteristics within the averaged VOC dynamics are identified. After that, the achievable power setpoints, P^* and Q^*, for each controlled inverter is determined by considering a set of security constraints. Then, the desired active and reactive output power of each inverter is achieved by continuously tuning two VOC parameters, i.e., the voltage scaling factor k_v, and current feedback gain k_i, respectively. In this article, as illustrated in Fig. 9, after comparing the power setpoints with the measured output power, PI controllers are employed to dynamically generate k_v and k_i.

F. Droop-Free Distributed Control

Different from centralized and decentralized control, sparse communication structure makes distributed control techniques a natural fit in controlling spatially dispersed DGs. Each agent (i.e., DG) exchanges data with its neighbors according to a specified communication protocol, leading to reduced computational complexity and hence, enhanced reliability. The communication structure is constructed based on graphic theory, which can be expressed as $G = (V, C, \boldsymbol{A})$ containing a nonempty finite set of nodes $V = \{v_1, v_2,..., v_N\}$, a set of edges $\mathcal{E} \subset V \times V$, and the adjacency matrix $\boldsymbol{A} = [a_{ij}] \in \mathbb{R}^{N\times N}$. The graph can be directed or undirected. The communication weights a_{ij} are design parameters. $a_{ij} > 0$ if Node i receives data from Node j and $a_{ij} = 0$, otherwise. To guarantee consensus or tracking among all nodes, the graph must have at least a spanning tree [67]. In a microgrid, each DG can be deemed as a node, while the communication links among DGs can be seen as edges. For instance, in a microgrid with a communication structure illustrated in Fig. 10, the adjacency matrix can be expressed as (17). The adjacency matrix encodes the microgrid cyber network topology, and it varies with the change of communication structure.

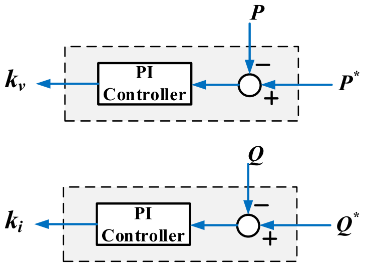


Fig. 9 Active and reactive power regulation by continuously tuning the current feedback gain and the voltage scaling factor of the VOC controller.

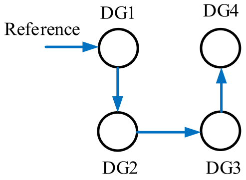


Fig. 10 Communication structure for distributed control.

$$A = [a_{ij}] = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}. \quad (17)$$

Based on the theory mentioned above, a droop-free cooperative distributed control paradigm is proposed in [31]. As illustrated in Fig. 11, the controller is comprised of three subsystems: 1) active power regulator, 2) reactive power regulator, and 3) voltage regulator. Each regulator processes its local measurement and exchanges information with its neighbors to update its frequency and voltage set points. The voltage regulator uses an estimator to find the global voltage magnitude, to be exact, the averaged voltage across every DG. The obtained average voltage is then compared with the nominal voltage e_{rated} and the error is sent to a PI regulator to produce the first term $\delta e^1{}_i$ for voltage correction. Meanwhile, in the reactive power regulator, the normalized reactive power is compared with those

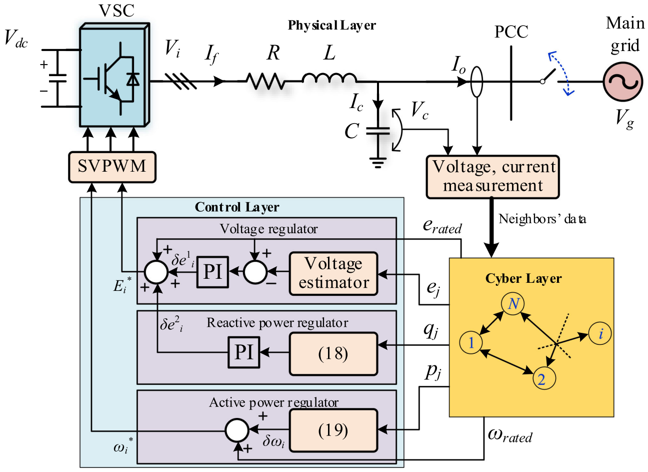


Fig. 11 Droop-free distributed cooperative control structure.

of its neighbors by using the following protocol to calculate the neighborhood reactive loading mismatch

$$mq_i = \sum_{j\in N_i} ba_{ij}\left(q_j^{\text{norm}} - q_i^{\text{norm}}\right) \tag{18}$$

where b is the control gain. This difference in reactive power is then delivered to another PI regulator that generates the second term for voltage correction $\delta e^2{}_i$. Thus, the voltage regulator incorporates with the reactive power regulator to determine the voltage set point by adding two correction terms to the nominal voltage.

The third subsystem, the active power regulator, is responsible for frequency and active power. It finds the active loading mismatch with the neighborhood to generate the correction term for frequency as

$$\delta\omega_i = \sum_{j\in N_i} ca_{ij}\left(p_j^{\text{norm}} - p_i^{\text{norm}}\right) \tag{19}$$

where the control gain in this protocol is c. This correction term together with the rated frequency generates the frequency set point and thus, the phase angle of the inverter

$$\omega_i^*(t) = \omega_{\text{rated}} + \delta\omega_i(t). \tag{20}$$

By using this protocol, the microgrid frequency eventually synchronizes to the rated frequency. The main merit of this distributed control is that proper load sharing, frequency synchronization, and global voltage regulation can be achieved simultaneously without relying on the droop mechanism or using additional secondary control. In addition, frequency measurement is not needed, and it can be effectively used as a general solution for various distribution systems with different power line *R/X* ratios. Notice that nonidealities, e.g., transmission delay, packet loss, and limited bandwidth may compromise the overall system performance. In actual implementation, low delay, less packet loss, and higher bandwidth communication are preferred to guarantee satisfactory control performance.

Since then, subsequent work regarding distributed control has been done. For example, to enable a seamless transition between islanded and grid-connected modes, a unified distributed droop-free secondary control is proposed for both grid-following and grid-forming inverters [32]. Similarly, the inverters can communicate via a sparse communication graph and exchange data with their neighbors. The main improvement in this article is that it can ensure accurate active and reactive power sharing among all grid-following and grid-forming inverters. In previous works, the average voltage of the system is controlled to be the rated voltage. However, regulating only the average voltage along a distribution line may not necessarily ensure that the voltage at a specified point can always vary within a range of ±5%, as specified by IEEE 1547 Standard. To guarantee an acceptable voltage profile and avoids any violation of voltage deviations, an improved droop-free distributed control consisting of a distributed voltage variance observer, an additional voltage variance regulator, and relaxed reactive power sharing is developed in [68]. Another important aspect in practice is the reliability issues in electrical and communication networks. To investigate these issues, the performance of the distributed control under both electrical and communication failures is analyzed in [33].

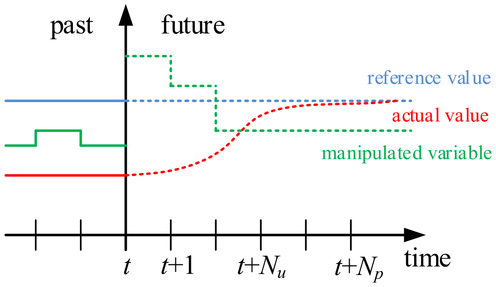


Fig. 12 Prediction and control principle of MPC.

G. Model Predictive Control

MPC, also referred to as moving horizon control or receding horizon control, can be traced back to the 1960s [69]. Since then, it had been developed gradually into a mature technique to deal with multivariable constrained control problems in the process-control industry. The MPC uses system models to predict future behaviors over an N_p-step time horizon and then a cost function subsequently as the criterion to select appropriate control actions. Fig. 12 illustrates the prediction and control principle. At the current point in time, an optimal plan is determined based on predictions and certain selection criteria. Then, only the first element of the optimal sequence is implemented, and subsequently, the horizon is shifted [70]. At the next sampling time, the new state of the system is measured or estimated, and a new optimization problem is solved using the new system behaviors. By using this receding horizon approach, a closed-loop feedback control that can compensate for disturbance is established to track the reference value. To reduce the calculational burden, an additional control horizon N_u can be introduced. After N_u steps, the control action will not be changed anymore. Due to the merits of flexibly formulating control objectives and constraints, MPC has been extensively applied in microgrids at the system level for a variety of objectives such as operational cost minimization,

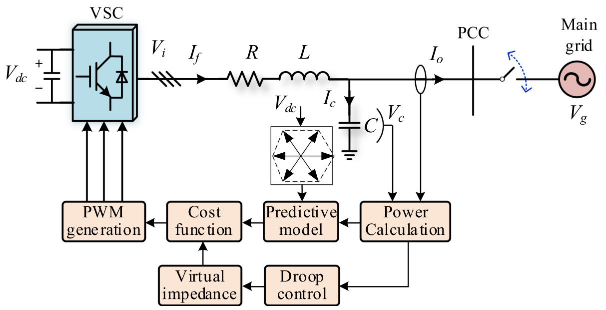


Fig. 13. Block diagram of MPC for parallel inverters.

power loss minimization, economic benefits maximization, optimal power dispatching, etc. [71]–[76]. In system-level MPC, the sampling period is usually in the scale of minutes or hours while the prediction horizon could be 24 h or even longer.

Regarding power converter control of microgrids at the device level, which is the focus of this article, MPC has also drawn much attention. Different from the process control, power converter circuits are nonlinear systems with ON/OFF switching states. Taking a conventional three-phase two-level voltage source inverter (VSI) for example, only eight voltage control vectors are available. To adapt to the discrete-time nature of power converters, finite-control-set MPC was developed for UPS systems, DGs and subsequently microgrids [77]–[80]. With the present state of the model, the discrete interval and the possible control actions as the inputs, the system's future status can be predicted. Usually, in power converter coordinated control in microgrid applications, a two-step prediction horizon is adopted due to the short sampling period in the scale of microseconds. Certainly, a longer prediction horizon can also be applied in FCS-MPC to achieve various performances such as reduced switching frequencies and enhanced stability, depending on the complexity of the algorithm and the computing capacity of the digital signal processors. Recently, most of the MPC methods applied in parallel converter operation for microgrids are focused on the replacement of the inner cascaded voltage/current structure with MPC algorithms, in which droop mechanism is retained [34], [35], [81]. As shown in Fig. 13, the power measurement and calculation are used both for the droop mechanism and the predictive model. Then, the virtual impedance can be added to the droop output before being sent to the cost function as the control reference. Meanwhile, the system's future behaviors obtained from the predictive model are delivered to the cost function. Since the outer power droop generates the required inverter output voltage for proper power sharing, the cost function can be formulated as follows:

$$J = \left(V_{c\alpha}^{*} - V_{c\alpha}(k+2)\right)^2 + \left(V_{c\beta}^{*} - V_{c\beta}(k+2)\right)^2 \tag{21}$$

where $V_{c\alpha}(k{+}2)$ and $V_{c\beta}(k{+}2)$ are the real and imaginary parts of the two-step predicted capacitor voltage by considering one-step delay compensation in digital implementation, respectively. $V_{c\alpha}^{*}$ and $V_{c\beta}^{*}$ mean the real and imaginary parts of the reference voltage obtained from the droop controller, respectively. The advantage of using MPC is a fast dynamic response in transients in power regulation and voltage stabilization. Also, compared to cascaded linear control structures, PID gain tuning and PWM modulation can be avoided.

Although high robustness and fast dynamic response can be obtained, circulating current is one of the challenges when using finite control set MPC. As pointed out in Section III, circulating currents will result in current/voltage distortion and additional power loss. Some research efforts have been reported to alleviate circulating currents. For instance, by adjusting weighting factors of the cost function properly, it is reported that the circulating current can be suppressed to a large extent in [36]. Specifically, the voltage vectors are categorized into two groups according to their contribution to the circulating current. Then, different weights are added to these vector groups to re-design the cost function. In this way, the advantages of MPC can be retained while circulating currents can be suppressed effectively. MPC has also been used to control parallel-connected multilevel converters. One such example is an MPC scheme developed for three-level T-type inverters with a reduced computational burden [82], [83]. The proposed methods can mitigate zero-sequence circulating current, neutral point voltage imbalance, and common-mode voltage simultaneously. However, the inverters are supplied by a common ac power source through *LR* filters without considering grid-forming and load-sharing operation. It is thus not suitable for microgrid operation. Another contributor to circulating current is the variable switching frequency in finite control set MPC. To achieve a constant switching frequency, virtual state vectors were added to the MPC controller in [37] to suppress the circulating currents.

Besides FCS-MPC, another important stream under MPC for power converters is CCS-MPC [84]. The best voltage vector in continuous form is obtained based on the prediction model and selection criteria. Then, modulation techniques such as space vector modulation (SVM) can be used to generate the corresponding switching signals to synthesize the desired output voltage. From the optimal control action selection point of view, CCS-MPC in power converter control is in line with the conventional MPC in the process industry with a longer prediction horizon. In [38], a CCS-MPC scheme for parallel operation of single-phase inverters without involving a droop mechanism is developed. A MIMO state-space mathematical model is derived to describe the parallel-inverter system. The cost function is formulated by considering voltage tracking and circulating current reduction as [38]

$$\begin{aligned} J = {} & \alpha \sum_{j=1}^{N_p} \left[V_o^{*}(kT+jT) - V_o(kT+jT|kT)\right]^2 \\ & + \beta \sum_{j=1}^{N_p} \sum_{l=1}^{n-1} \left[i_l(kT+jT) - i_{l+1}(kT+jT)\right]^2 \\ & + \left[i_n(kT+jT) - i_1(kT+jT)\right] \\ & + \lambda \sum_{j=1}^{N_u} \left[\Delta u(kT+jT-T)\right]^2 \end{aligned} \tag{22}$$

where n is the number of inverters; V_o is the prediction of the output voltage of the system; T is the sampling period; α, β, and λ are the weighting factors. Notice that the third term is the

TABLE II
PERFORMANCE EVALUATION OF CONTROL METHODS FOR COORDINATION OF PARALLEL POWER CONVERTERS

Control categories	**Algorithm complexity**	**Communication requirement**	**Voltage/frequency deviations**	**Dynamic response**
Concentrated control [4]-[6], [54]	Low	High	Low	High
Master-slave control [7]-[9], [55]-[57]	Low	Medium	Low	Medium
Droop control [12]-[19], [58]-[60]	Medium	Low	High	Low
VSG [20]-[24], [63]-[65]	Medium	Low	High	Low
VOC [25]-[30], [66]	Medium	Low	Low	High
Droop-free distributed control [31]-[33],[68]	Medium	Medium	Medium	Medium
MPC [34]-[38], [81]-[83]	High	Medium	Low	High

quadratic measure of the control effort to limit large control-signal variation. By minimizing the cost function, the optimal control signal is produced and then a PWM modulator is used to generate the gate drive signals for the inverters with constant switching frequencies. One of the shortcomings of this work is the neglect of line impedances in distribution networks in the MIMO state-space model, which consequently may affect power sharing and voltage quality in practice. To date, in parallel operation of distributed inverters, there has been limited research work on CCS-MPC compared with FCS-MPC. Considering its distinct merits, CCS-MPC will likely attract increasing attention and show promising potential in microgrid applications.

For better comparison, Table II provides further evaluation assessment regarding the performance of various control techniques in terms of algorithm complexity, communication requirement, voltage/frequency deviations, and dynamic response.

V. FUTURE TRENDS

A. Distributed Cooperative Control

With the rapidly increasing DG units in future smart microgrids, centralized schemes may not be able to operate because of the security vulnerability and computational burden. By contrast, distributed control techniques do not require central control units with high bandwidth communication. It is based on sparse communication networks in which each DG processes its local measurement and exchange information with its neighbors to update its voltage magnitude and frequency set points. Because distributed cooperative control structures are aligned with the plug-and-play feature and spatially dispersed configurations of DGs, it becomes a natural fit to address their reliability and expandability requirement, showing promising applications in microgrids. Particularly, finite-time consensus-based strategies and distributed MPC approaches with less communication burden may attract increasing attention and will be applied more widely due to the capability of dealing with disturbances and uncertainties.

B. Ancillary Grid Support

A microgrid formed by a variety of DGs can be controlled to provide ancillary services to the main power network, such as reactive power compensation, generation scheduling optimization, voltage and frequency regulation, enhanced system control and dispatch services, black-start restoration, and energy imbalance compensation. From the perspective of power electronics, the capability for providing ancillary services by a microgrid is dependent on the capacities and the degree of control freedom of the power converters [85]. Also, a microgrid can provide extended ancillary services if ESS systems are installed.

C. Artificial Intelligence (AI)

AI is capable of humanlike learning and reasoning to solve complex problems. Currently, AI technology is advancing at a fast rate in computer science, and it has recently brought a new frontier in modern power electronics [86]. With increased penetration of DERs, microgrids tend to become more and more complex and hence, difficult to manage manually. Thus, self-operating systems should be designed to make decisions and respond to events in microgrids without human intervention. In this sense, we expect that AI methods such as artificial neural network, expert system, fuzzy logic, and machine learning can find their promising applications in power converter control in microgrids.

D. Power Converter Control for E-Mobility

The future e-mobility consists of EVs, charging infrastructures and information systems. It is expected that EVs will be reshaping the transportation sector as well as the distribution network in the coming years. After a decade of rapid growth, the global electric car stock hit the ten million mark in 2020. The largest manufacturers worldwide have declared electrification targets and committed to increasing the offer and sales of EVs for 2030 and beyond [87]. While high EV penetration poses challenges in the context of microgrids, the flexibility of EVs in terms of charging/discharging rates, durations, and schedules can be explored to avoid renewable energy curtailment and stabilize the distribution networks [88], [89]. Fig. 14 depicts a schematic diagram of e-mobility. The real-time information including power generation, load demand, EV state of charge, driver destinations, voltage quality at different points along the power grid, etc., will be sensed and sent to the energy management system via local area network. After that, charging commands based on optimization will be delivered back to individual EVs. To achieve this, the development of smart chargers, which are essentially power electronic converters, will be critical. From this perspective, the authors believe advanced power converter control algorithms specified for e-mobility will become one of the major research streams under the smart microgrid architecture.

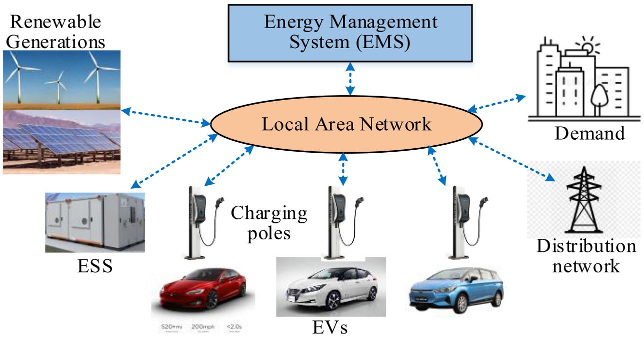
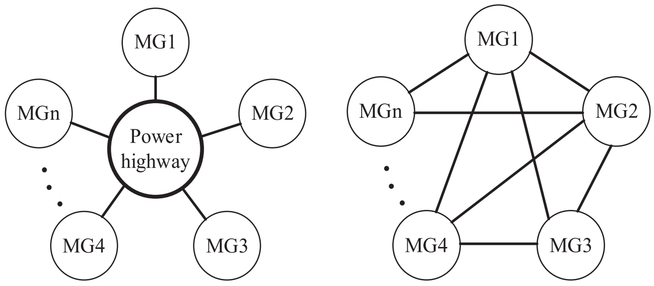


Fig. 14 Schematic diagram of management and control of e-mobility.



(a) (b)

Fig. 15 Two potential configurations of future networked microgrids. (a) Interconnected via a common power highway. (b) Interconnected via a sparse power network.

E. Power Converter Control for Networked Microgrids

With the increasing penetration of DERs and EVs, the next generation power grid tends to be a decentralized infrastructure consisting of networked microgrids, where power shortfall in one microgrid can be compensated by the excess power available from its neighbors. Fig. 15 shows two potential configurations of future networked microgrids. Individual microgrids exchange energy with others through power highways or spare power networks by controlling the interlinking voltage source converters. In this context, the control of power converters, which not only serve as an electronic interface between power sources and the grid within individual microgrids but also as energy interchanging hubs among networked microgrids, will become more crucial and challenging.

VI. CONCLUSION

With the rapidly increasing penetration of DERs into microgrids, power electronic converters are required to present a high degree of intelligence and operate effectively to improve power quality and maintain dynamic stability. This article presented an overview of power converter control techniques for microgrids. It aims to provide insights into the existing technical challenges in power converter control in microgrids. In addition to the droop mechanism, the most important control schemes, including concentrated control, master–slave control, VSG, VOC, droop-free distributed cooperative control, and MPC, are highlighted and analyzed in detail. Their advantages and shortcomings are discussed. Compared to centralized and master–slave control approaches, droop-based control methods can avoid communication links among DGs and, hence, help enhance system reliability. However, droop control methods do not provide inertial support to the power network, leading to frequency stability issues. To address this problem, VSG can be a good alternative. And it is found that droop control is actually a special case of VSG with zero virtual inertial and zero damping factor. Droop-free distributed control is another good alternative. The sparse communication structure and its ability of accurate power sharing and voltage deviation mitigation make it a natural fit in controlling spatially dispersed DGs in microgrids. Among the recent development, VOC and MPC are two promising control schemes. Specifically, VOC requires only local current measurement and shows fast dynamic response while MPC presents excellent dynamic response as well as the ability of including different control objectives and constraints. A wider application of VOC and MPC in microgrids is yet to be seen and their feasibilities need to be further demonstrated by considering more practical network aspects. Finally, future research trends for power converter control techniques in microgrids are discussed. It is expected that distributed cooperative control, together with AI techniques, may become a major research topic. And microgrids with ESSs and EVs are promising to provide ancillary grid support and accommodate renewable energy integration.

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