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REVIEW

A review of recent control techniques of drooped inverter-based AC microgrids

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Abstract

As the penetration of distributed generation (DG) systems in the grid is increasing, the challenge of combining large numbers of DGs in the power systems has to be carefully clarified and managed. The control strategy and management concept of the interconnected systems should be flexible and reliable to handle the various types of DGs. This can be suitably met by microgrids. This paper introduces the microgrid structure and elements and states the main objectives that should be achieved by the microgrid controllers and each DG controller in both operation modes (grid-connected and island mode). It also presents the challenges of having multiple DG units in a microgrid in terms of accurate power control/sharing, voltage and frequency regulation, power management between DGs, different renewable energy sources integration and deployment, seamless mode transfer, and the modeling issues. The centralized and decentralized control techniques as potential solutions have been discussed and compared by highlighting the advantages and disadvantages of each. Furthermore, the recent control techniques for drooped alternating current microgrids and the main proposed solutions and contributions in the literature have been exposed to finally overcome the droop control limitations and obtain a flexible and smart distributed power system.

KEYWORDS

distributed generators, droop control, inverters, microgrid

1 | INTRODUCTION

The interest in distributed generation (DG) systems is rapidly increasing because larger power plants are becoming less feasible in many regions due to increasing fuel costs and stricter environmental regulations. In addition, recent technological advances in small generators, power electronics, and energy storage devices have provided a new opportunity for distributed energy resources at the distribution level. Traditional centralized power generation systems have many drawbacks: first, power generation plants depend heavily on fossil fuel, which increases CO_2 emission and the rejected heat is wasted; second, a large amount of power is produced in one place and delivered using expensive transformers and transmission lines; third, transmission lines and transformers create the well-known problems of power losses and voltage drop; fourth, traditional centralized power generation does not provide an economically feasible solution to supply power to poor and isolated communities.

DG systems considered in the literature are typically nonconventional and renewable energy sources (RESs), such as fuel cells, biomass, geothermal, photovoltaic (PV), wind, and microturbines.[1–3] RES integration contributes to reducing CO_2 emissions from fossil fuel-based sources, reducing transmission losses, mitigating voltage variation, relieving peak loading, and enhancing supply reliability. However, increased penetration of DG sources, particularly in the distribution network, may cause problems such as voltage rise, unstable voltage, frequency, and protection miss-coordination.[4–7] Such problems can be mitigated by aggregating a number of DG sources and loads into one controlled unit called a microgrid as shown in Figure 1. A microgrid has many advantages, such as increased reliability, more controllability, and better power quality. Like a traditional power grid, smart microgrids generate, distribute, and regulate the flow of electricity to consumers, but do this locally. It can be seen as a modern, small-scale version of the centralized power generation system. The IEEE Std. 1547.4[8] presents the microgrid concept as a cluster of DG units connected to a distribution network to maintain the reliability of critical loads, mainly when the grid supply is not available.

Energy sources, such as solar PV, wind turbines, gas microturbines, and energy storage systems (ESSs), such as batteries, cannot be readily interfaced to the grid being direct current (DC) (PV and batteries) or variable alternating current (AC) frequency (wind turbines and gas microturbines). Therefore, power electronic converters are required to interface these sources to the grid. The grid interface DC/AC power electronic inverters are paralleled together to form one AC bus which is connected to the grid via a Static Transfer Switch (STS) that can be monitored and controlled by the microgrid central controller (MGCC) and could alternatively be called a supervisory controller (SC)[10,11] or energy management system (EMS).[12,13] The latter also sends all DG configurations and set-points of voltage, frequency, and power through a low-bandwidth communication link. Local loads can be connected to the microgrid side of the STS. The microgrid has two modes of operation: grid-connected mode and island mode. In grid-connected mode, the DC/AC inverters are connected in parallel with the grid and hence the bus frequency and voltage are fixed by the stiff grid.[14] In this mode, inverters can export/import power to/from the grid. If the STS opens, the microgrid operates in island mode. In this mode, the output voltage and frequency are controlled by the DC/AC inverters, and the local load is supplied by the paralleled inverters which share the load equitably, that is, each unit shares power according to its rating. The microgrid can transfer from grid-connected mode to island mode as well. This transfer is called islanding which could be intentional and unintentional. Intentional islanding happens due to a preplanned decision and the STS opens at a predefined moment. Normally all precautions will be taken to make this intentional transition from grid-connected mode to island mode as smooth as possible.[15] Unintentional islanding, however, can occur at any time, because of a sudden fault in the utility grid. This type of islanding might cause undesirable transients and robust design

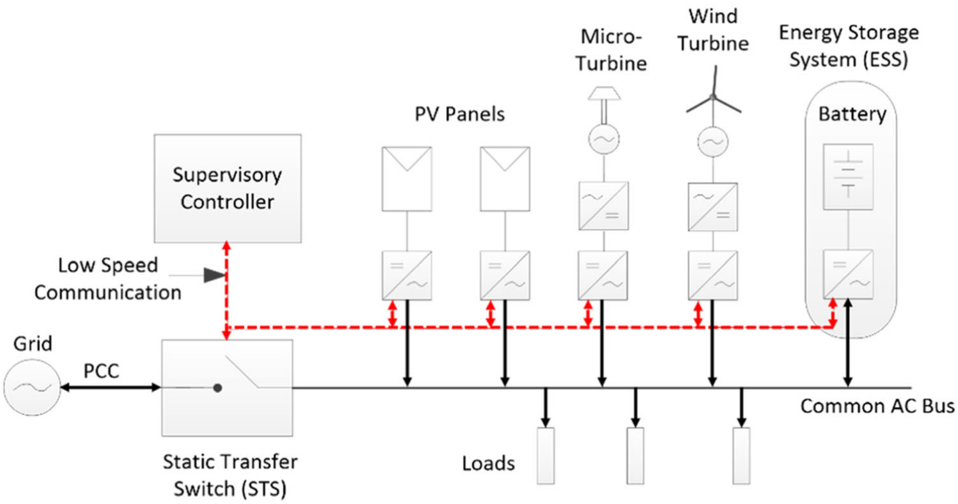

FIGURE 1 Microgrid structure of multiparallel DC/AC converters supplied by renewable energy sources.[9] AC, alternating current; DC, direct current; PCC, point of common coupling; PV, photovoltaic.

should be embedded.[16] The microgrid can also transfer from island mode to grid-connected mode. The STS senses the voltages at both of its terminals and only closes when these voltages are synchronized.

The challenges of having multiple DG units in a microgrid should be addressed to achieve the following objectives:

1. Without interrupting the grid or the microgrid operation, other energy sources can be integrated and installed smoothly.
2. Power management, monitoring, and optimization can be implemented to be decentralized or centralized according to a user-defined plan, the economy, or any certain standards.
3. Coordinating seamless transfer between both modes of operation (grid-connected and island) without tripping any unit or disturbing the system stability.
4. Improving system reliability and flexibility by deploying many energy sources options as storage, renewable or nonrenewable sources.
5. Providing fast response against any load demand, which includes accurate power sharing, voltage and frequency regulation and power quality requirements to be embedded in each DG.
6. Mitigating the need for communication is essential for low-cost solutions, in particular, between the DGs themselves.

The field of drooped inverter-based AC microgrids has demonstrated a notable growth in research interest over the past decade. The data collected from Google Scholar, in Figure 2, shows a consistent increase in the number of publications from 2010 to 2022, indicating an expanding body of research in this area.

Starting from 329 publications in 2010, there has been a steady upward trajectory, reaching 4410 publications by 2022. This trend reflects the escalating importance of drooped inverter-based AC microgrids in the context of renewable energy integration and smart grid development. The significant rise in publications, particularly from 2015 onward, suggests a heightened focus on addressing the challenges and innovations in microgrid technologies, including aspects of control, stability, and efficiency.

The year 2023 shows a slight decrease in publications, which could be attributed to data being collected partway through the year. However, the overall trend from 2010 to 2022 underscores the field's dynamic evolution and its critical role in advancing sustainable energy systems.

In summary, the increasing number of publications over the years highlights the growing research interest and continuous advancements in drooped inverter-based AC microgrids, underscoring their significance in the modern energy landscape.

In the rapidly evolving field of microgrid control systems, particularly focusing on drooped inverter-based AC microgrids, it is crucial to distinguish the unique contributions of this work from existing literature. While comprehensive reviews[17–21] along with other significant works, like, Rokrok et al.[22] on primary control methods for islanded microgrids, Gonzales-Zurita et al.[23] on multiobjective control strategies, Chungu et al.[24] on voltage and frequency control, and Espina et al.[25] on distributed control strategies, have significantly contributed to the field, our paper specifically addresses the recent advancements in drooped inverter-based AC microgrids. Our focus extends beyond the scope of these works by encompassing both islanded and grid-connected modes, highlighting the integration challenges

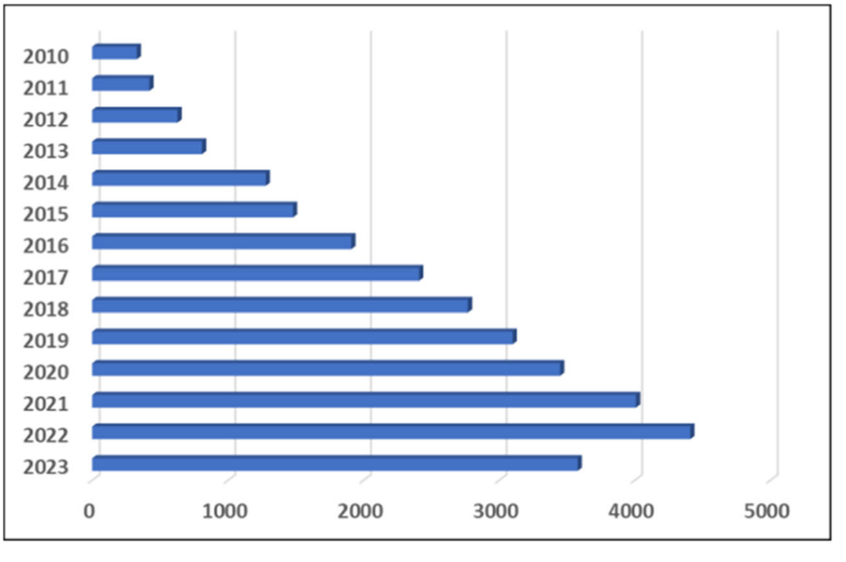

FIGURE 2 Number of publications on drooped inverter-based microgrids until November 2023.

of multiple DG units, and providing a detailed comparison of centralized and decentralized control techniques. This paper aims to fill a critical gap in the current literature by offering a detailed and updated analysis of the challenges, solutions, and future trends in the control of drooped inverter-based AC microgrids, thus presenting a unique and valuable perspective to researchers and practitioners in the field.

This paper reviews the control techniques of drooped inverter-based AC microgrids to achieve the above-mentioned objectives and challenges. Section 2 presents the various operation modes of the DG system in a microgrid and the needs of storage systems in Section 3. Section 4 discusses the features of centralized and decentralized systems. Sections 5–7 introduce to droop control and its limitations. Section 8 reviews the recent techniques for drooped AC microgrids, including output power control, voltage and frequency regulators, and supervisory power management strategies.

2 | DGS OPERATION

Although the inverter-based microgrid can work as a stand-alone system in island mode, the inverters are classified into three control classes as follows:

1. *Grid-forming units*: The DG under this category is designed for autonomous operation representing an ideal AC voltage source with a fixed output frequency as shown in Figure 3A. It contains a closed-loop controller to achieve steady-state values and robust disturbance rejection. Grid-forming units regulate the system voltage and frequency through balancing the generation power and load demands when the microgrid operates in the island mode.[26] However, in the grid-connected operation mode, as there are voltage and frequency references from the main grid, the grid-forming units are changed to operate as grid-feeding units. Hence the control methods for grid-forming units should be suitable for both microgrid operation modes, so as to ensure the smooth transients during the microgrid mode changes.[27]
2. *Grid-feeding units*: This DG is designed to control the output current/power which has a synchronized frequency with the main AC bus representing an ideal current source as shown in Figure 3B. It does not contribute to microgrid power balancing.[28] Majorly, this control scheme used for PV and wind integration applications, in particular, in grid-connected mode.[29] Here, the output voltage control is not an objective as it is fixed by another forming unit or the grid.
3. *Grid-supporting units*: In which the DG is a controlled voltage source that is designed to control its output voltage and frequency to allow power sharing and managing in both microgrid modes of operation. It represents a voltage source with output impedance, Figure 3C, and the voltage and frequency are no longer fixed but subject to the required active and reactive output power. This class also can work as a voltage source or a current source according to the adopted control scheme. It gathers the features of grid-forming and grid-feeding units that allow seamless transfer and operation switching.

Alternatively, in the literature, DGs can be classified as voltage or power-controlled sources (PCSs) as follows:

1. The voltage-controlled source (VCS) is designed to regulate its voltage and frequency and to act like a grid so it is a grid-forming unit or it can manipulate its voltage and frequency for power sharing/balancing and here it is a grid-supporting unit.[30,31] This mode of operation is called also *V*/*f* mode where *V* and *f* are set internally.
2. The PCS controls its output power/current where the bus is regulated by another forming/supporting unit or the grid. This mode is called also *P*/*Q* mode. In the case of controllable energy sources like fuel cells and microturbines, the power set-points are provided by the MGCC. However, for RESs like PV and wind, the power set-points are set according to the available

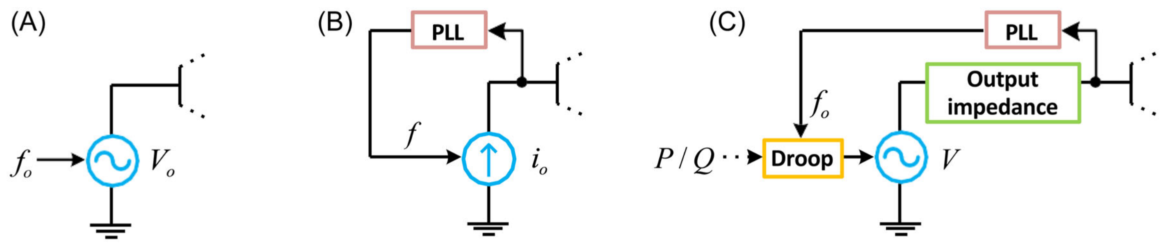

FIGURE 3 Classification of DG units operation in a microgrid. (A) Grid-forming, (B) Grid-feeding and (C) Grid-supporting units.

output power. Techniques like maximum power point tracking (MPPT)[32] are used commonly for this case.

The control objectives, strategies, and applications for the DG unit's operation classification are shown in Table 1.

3 | NEEDS OF ESS

The power demand and load supporting are mainly can be provided by the grid in grid-connected mode. The microgrid here just injects the available power without caring about the demand as the grid will compensate for any voltage and frequency variations. However, the energy source in a DG operating as a grid-supporting unit is crucial to compensate for any disturbances in voltage or frequency in island mode.[33] In addition, the slow response of some of RES should be noted during any load demands. Energy storage devices, that is, batteries, are commonly connected to the DC-link to supply/absorb power during transients while the RESs are controlled to ramp up/down the output power to match the supplied power at a steady state.[16,34] Therefore, ESS is the main component to rely on for the feasible operation of a microgrid despite its space, cost, and maintenance requirements.[35]

4 | CENTRALIZED AND DECENTRALIZED POWER MANAGEMENT STRATEGIES

One of the main control objectives in a microgrid is to achieve reliable power management while maintaining close regulation of the microgrid voltage magnitude and frequency. The power management strategies can be categorized into centralized and decentralized strategies, Figure 4, as follows:

1. In centralized power management, the SC or EMS unit is directly responsible for coordinating the DG units to maintain the power balance in an island microgrid at a steady state.[36] Therefore, supervisory power management algorithms and high bandwidth communication are crucial to coordinate the operation between the DG units. Although, each DG unit has primary controllers which receive external references from MGCC to manage the power at a steady state, at least a single master unit must be responsible for regulating the voltage and frequency of the AC bus. In addition to the high dependency on the communication in these strategies, which is costly and decreases the system reliability and expandability, it is subject to a single point of failure. Moreover, it does not provide seamless mode transition from grid-connected mode to island mode and vice-versa. During the transition, the voltage across the load can become very low or very high.[37]
2. In decentralized strategies, the DG's primary controllers are responsible for maintaining the power balance in the island microgrid autonomously without requiring external information. However, the MGCC can still be used to improve the performance of the microgrid. These strategies in the literatures[38–43] are based on the droop control.

In the literature, other names like single-master operation and multimaster operation,[40,44] wired and wireless control schemes,[45,46] supervisory and autonomous control,[47] and concentrated and distributed control[18] are used alternatively denoting the centralized and decentralized operations. As a summary, Table 2 lists the advantages and disadvantages of centralized and decentralized systems.

TABLE 1 Comparison between the classifications of distributed generation units operation in a microgrid.

	Grid-forming	Grid-feeding	Grid-supporting
Control objective	Voltage and frequency regulation	Active and reactive power injection	Power balancing and sharing
Control strategy	Voltage, current, and frequency controllers	Output power controllers	Centralized and decentralized controllers
Operation analogy	Ideal voltage source	Ideal current source	Ideal voltage source with output impedance
Application	Stand-alone	Grid-connected	Grid-connected and island
Control mode	*V/f* mode	*P/Q* mode	Drooped *V/f* mode

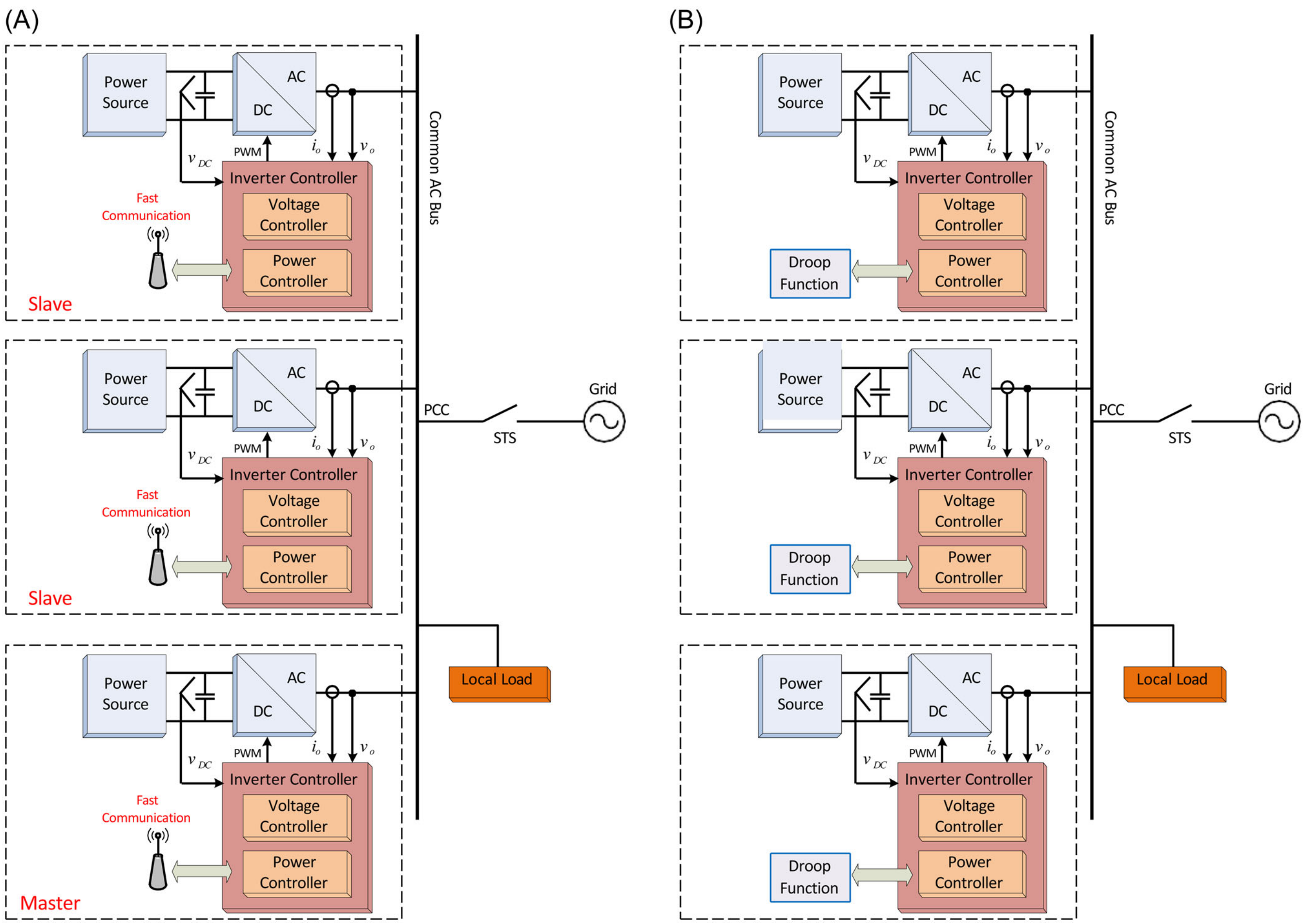

FIGURE 4 Microgrid control scheme strategies: (A) centralized and (B) decentralized. AC, Alternating Current; DC, Direct Current; PCC, Point of common coupling; PWM, pulse-width modulated; STS, Static Transfer Switch.

TABLE 2 Advantages and disadvantages of centralized and decentralized systems.

	Advantages	Disadvantages
Centralized topology	– Good voltage/current and frequency regulation – Accurate power control in grid-connected mode – Accurate power sharing in island mode	– Supervisory power management algorithms are crucial – High bandwidth communication is required – Low redundancy, reliability, and expandability – Subject to single-point failure – Rough mode transfer support – Asymmetric control schemes for each unit
Decentralized topology	– Achieve power sharing wirelessly – Support plug-and-play ability – Seamless mode transfer support – Symmetric control schemes for each unit	– Poor power-sharing accuracy – Degrade the voltage and frequency steady-state values – Still needs a low-bandwidth communication bus – Needs supervisory control for grid connection transfer

5 | DROOP CONTROL

Decentralized parallel structure relies on the ability of the DG unit to regulate the output voltage and frequency while sharing the active and reactive power demands. A key for wireless technique is to use droop control,[48–50] which is widely used in conventional power generation systems. Since there is no synchronous machine in most microgrids to achieve demand and supply balancing, the inverters should be responsible for mimicking the synchronous machines behavior by enabling the use of VSC to provide voltage and frequency references based on the output active and reactive power.[16,51–54] The advantage is that no external communication mechanism is needed among the inverters. However, communication can still be used between each unit and a supervisory central controller for monitoring and optimizing issues. This eases the control implementation, based merely on local voltage and current information, and enables plug-and-play operation. Thus, it increases redundancy and simplicity of system expansion.

The two modes of operation for microgrids are equally important; however, the island mode is emphasized because it is particularly more challenging.[55] In grid-connected mode the control of power generated to the grid can be easily implemented using droop control or other direct controllers.[56,57] However, the strength of droop control appears in island mode, when all units need to share power according to their rating without the need to communicate with other units. This supports the seamless transfer between the microgrid modes as well.[37] Figure 5 illustrates the power system flow between two voltage sources separated by an inductor and how the active power can be controlled by the phase angle between the voltage signals of each source and controlling reactive power by changing the amplitude difference between these sources.

The active and reactive power that is exported from each inverter is subject to one of the two forms according to the type of output impedance.

The output impedance can be dominantly inductive or resistive and this determines how the inverter would control the exported power. When the inverter's output impedance is pure inductive, the generated active power (P) depends on the phase difference (δ) between each inverter output voltage (V_{inv}) and the PCC voltage (V_g) while the reactive power (Q) depends on the magnitude difference between the voltages ($V_{inv} - V_g$). The situation is inverted if the system impedance is pure resistive as shown in Table 3. In practical scenarios, the output impedance cannot be purely inductive as a resistive value might affect its performance.[58]

The natural form for the output impedance is the inductive case. This is valid in three-phase lines that are mainly inductive and in single-phase lines when an extra grid inductor is adopted.[59] Thus, the active power will be controlled according to the phase angle while the reactive power will be controlled by the voltage difference as explained earlier. Figure 6 shows the relationship between $P-\omega$ and $Q-V$.

The role of the droop control here is to govern the output power to make eventually a good power sharing between inverters in the case of islanding and accurate controlling of the injected power to the grid in the case of grid-connected mode.[60–64] For each case (grid-connected, island modes) the droop control equations are as follows:

In island mode,

$$\omega = \omega^* - K_\omega P, \tag{1}$$

$$V = V^* - KaQ, \tag{2}$$

where K_ω and K_α are the droop coefficients, ω^* and V^* are the frequency and voltage at no load, and P and Q are the measured active and reactive output powers, respectively.

In grid-connected mode,

$$\omega = \omega^* - K\omega(P - P^*), \tag{3}$$

$$V = V^* - Ka(Q - Q^*), \tag{4}$$

TABLE 3 Active and reactive power of parallel inverters.

Power control	System impedance: Pure inductive $Z_o = jX$	Pure resistive $Z_o = R$
Active power	$P \cong \frac{V_{inv}V_g\delta}{Z_0}$	$P \cong \frac{V_{inv}(V_{inv}-V_g)}{Z_o}$
Reactive power	$Q \cong \frac{V_{inv}(V_{inv}-V_g)}{Z_o}$	$Q \cong \frac{-V_{inv}V_g\theta}{Z_o}$

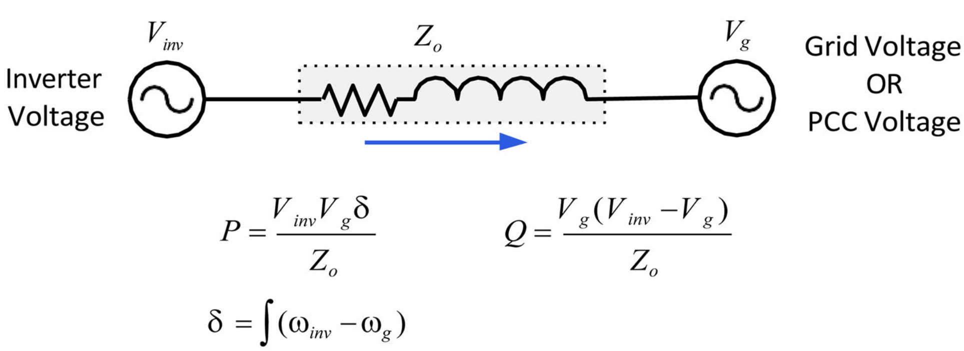

FIGURE 5 Power flow control between two voltage sources nodes. PCC, Point of common coupling.

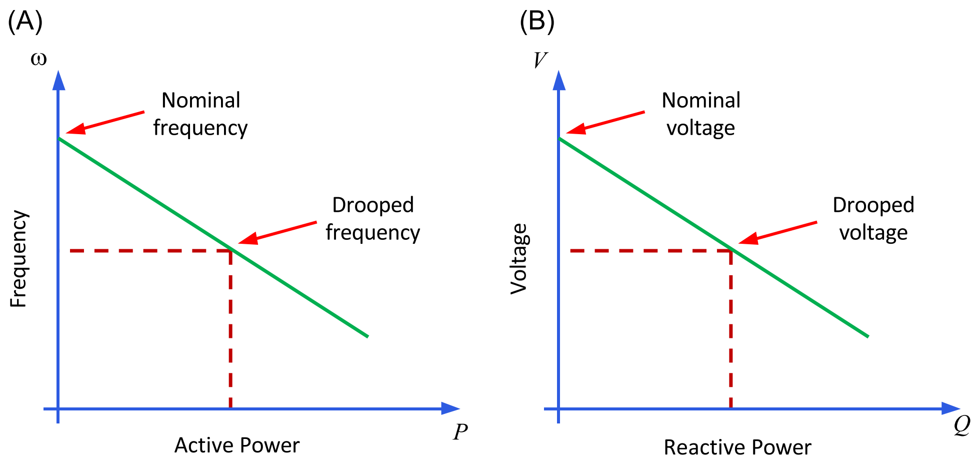

FIGURE 6 (A) $P-\omega$ and (B) $Q-V$ droop control curves.

where P^* and Q^* are the set-points of the required exported active and reactive power, respectively, and these settings are sent by the MGCC.

Active (P) and reactive (Q) power can be measured and averaged over one cycle of the fundamental frequency, so that the powers are evaluated at the fundamental frequency. This operation can be realized by means of low-pass filters (LPFs) with a reduced bandwidth.[65] Figure 7 shows the block diagram of the droop controller with measurement filters.

6 | DROOP CONTROL LIMITATIONS

Although the droop control introduces an intelligent automated method to control the power sharing/injection without communications between the inverters, its drawbacks limit its applications,[66,67] which include:

1. It has an inherent trade-off between load-sharing accuracy and voltage regulation as it introduces frequency and voltage variations proportional to the active and reactive output power.
2. The dynamics of the power sharing do not only depend on the droop control coefficients but also on the method of power calculation as using the LPFs creates new limits.
3. A restoration operation is needed before returning to grid-connected mode because of the drop in frequency and voltage caused by droop control, which reduces the mode transfer smoothness.
4. Droop control uses an assumption of pure inductive or pure resistive output impedance which is practically not very accurate. The output impedance could be a combination of both as complex impedance. This weakens the decoupling between the active and reactive power control loops because each pure form of the output impedance gives another form of droop control as stated in Table 3 and a combination of the two forms makes, for instance, any change in the frequency leads to a change in both active and reactive output powers. This is related also to the nature of the distribution network as shown in Table 4.[68]
5. Droop Control is not effective when the units supply nonlinear loads because it does not support the harmonic signals sharing.

7 | PRACTICAL CHALLENGES AND CONSIDERATIONS IN IMPLEMENTING DROOP CONTROL IN MICROGRIDS

The implementation of droop control in microgrids, while theoretically sound, encounters several practical challenges that can significantly impact its effectiveness and efficiency. This section delves into these challenges, drawing insights from both academic literature and industry practices.

1. *Parameter tuning and stability concerns*: One of the primary challenges in implementing droop control is the tuning of control parameters. Achieving optimal settings that ensure stable operation across various load conditions and high renewable penetration is complex. Instability issues, such as oscillations in voltage and frequency, can arise if parameters are not appropriately tuned.[69,70]
2. *Communication infrastructure limitations*: In many microgrids, especially those in remote or islanded locations, the communication infrastructure can be limited or unreliable. This limitation poses a

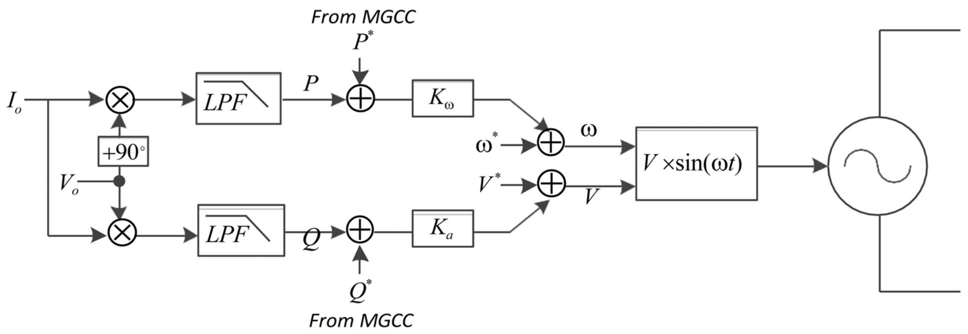

FIGURE 7 Diagram of droop control operation. LPF, low-pass filter; MGCC, microgrid central controller.

TABLE 4 Typical line impedance values.

Line type	R (Ω/K m)	X (Ω/K m)	R/X
Low voltage line	0.642	0.083	7.7
Medium voltage line	0.161	0.19	0.85
High voltage line	0.06	0.191	0.31

significant challenge for droop control strategies that rely on communication for coordinated control.[71]

3. *Integration with RESs*: Integrating intermittent RESs like solar and wind with droop control systems presents challenges in maintaining power quality and system reliability. The variability of these sources can lead to fluctuations in power output, complicating the droop control dynamics.[72]
4. *Scalability and interoperability issues*: As microgrids grow in size and complexity, scaling droop control strategies becomes increasingly challenging. Ensuring interoperability among diverse components and energy sources within a larger system requires careful planning and design.[73]
5. *Economic and regulatory hurdles*: Economic considerations, such as the cost of implementing and maintaining droop control systems, and regulatory hurdles, including compliance with grid codes and standards, can also impact the practical application of droop control in microgrids.[18]

8 | RECENT CONTROL TECHNIQUES FOR DROOPED AC MICROGRID

Many published works on microgrids have been mostly on improving control functions and strategies to achieve robust voltage and frequency regulation with optimized and accurate power sharing and enhancing the expandability within the microgrid stability margins. In the next sections, the main research contributions on droop control-based AC microgrid will be reviewed. The research outcomes are categorized into four categories according to the scope of each work as follows.

8.1 | Voltage/current controller

Different applications can deploy the DG as a VCS or PCS according to the energy source capability and the mode of the microgrid operation. In any case, each inverter mostly contains voltage and/or current control loops. The frequency usually can be chosen to be a fixed value, that is, in stand-alone operation, or subject to an outer loop, that is, PLL or droop control.[74] In the literature, as a PCS, a current control loop is designed to inject a referenced current value. As a VCS, the current loop is controlled by an outer voltage loop realizing a double voltage control loop which introduces quite enhanced performance in terms of speed, robustness, and disturbance rejection compared with a single loop voltage control which suffers from resonance issues and low stability margins.[75]

Many techniques have been adopted to implement the voltage\current controller as follows:

1. Xuehua et al.[76] proposed a proportional integral (PI) design based on Jury stability criterion for a current PI controller while Ortega et al.[77] proposed a PI voltage controller based on bode-blot analysis.
2. Proportional resonant controllers are used to cancel the steady-state error and attenuate the harmonics when the control variables are sinusoidal.[78–80]
3. Repetitive control (RC) is capable of tracking periodic references and rejecting periodic disturbances, which introduces high gain at all fundamental and harmonics frequencies.[81] However, the performance can degrade significantly in the case of grid frequency variation.[82]
4. Predictive control is developed to rid of the current steady-state error.[83] However, it is sensitive to the system parameters changes and advanced techniques

developed parameter estimation algorithm to increase its robustness[84] or presented adaptive algorithm.[85]

5. Hysteresis control is designed to force the current to track a reference value[86] based on hysteresis comparators. It does not have a fixed switching frequency and therefore a wide frequency spectrum is generated with a higher current ripple. However, it is easy to implement and has fast response and many works developed algorithm to obtain fixed switching frequency as in many studies.[86–88]
6. Deadbeat control has a very fast response and it is widely used for current control but it is not robust against parameters mismatch.[89] Many researches have been done to boost its robustness in many studies[90–92] but the structure of these controllers become more complex.
7. Other control topologies also have been proposed like sliding mode controller,[93] LQG/LQR,[94] H^{∞},[82] and fuzzy controllers[95] which can be reviewed in Bouzid et al.[96]

To mitigate the generated output filter resonance, active and passive damping techniques have been developed[97] and double loop control is widely employed in the literature. The passive techniques are power consumers and bulky whereas the active techniques are virtually implemented loops with more flexibility and efficiency. Large penetration of PV in grid-connected mode has been addressed in He et al.[75] in terms of the number of inverters and resonance generation which has been mitigated by a robust active damper. The stability issue is a concern in island mode, in particular, where the impedance of the distribution cables is not negligible and degrades the output voltage/current quality. In Corradini et al.,[98] the interaction between uninterruptible power supplies was investigated. The study recommended reducing the voltage controller bandwidth by manipulating the voltage and current controllers' gain to keep the system stable. In Wang et al.,[99] the controller bandwidth was reduced by using a feed-forward loop. Wang et al.[99] also concluded that a resistive virtual impedance has no effect on the system stability. However, the effect of inductive virtual impedance associated with cable lengths was not addressed.

8.2 | Droop control enhancement

The droop control limitations led the research toward developing techniques and controllers to enhance the performance of it. The outcomes of these researches can be categorized as follows:

8.2.1 | Dynamics of power control

The output power is subject to the available power in the case of RES supply or to a reference value in the case of ESS or nonrenewable supply. The dynamics of power export or import are very important during the grid/microgrid connection or any load demand steps, which expose the circulating current issues between the DGs. Many publications[82–84] proposed solutions to enhance the transient responses of active and reactive power sharing in grid-connected mode and island mode. Guerrero et al.[65] proposed a proportional–integral–derivative controller instead of just being a proportional controller to improve the dynamic response. Avelar et al.[100] proposed an extra phase loop to mitigate the response transient peak and to minimize the circulating currents between inverters. Adaptive droop controllers are proposed in many studies[101–103] to boost the performance and provide seamless mode transfer. The drooped frequency is mostly affected by the variations in load and generation power[104] and also in the unintentional islanding cases when it might cause unreliable system.[16] For that scenario, the anti-islanding controller should not take more than 2 s according to the IEEE Standard 1547.[8] If one inverter imports power during this period, the DC link voltage will rise and might exceed the maximum limit. This will cause the inverter to shut down to prevent any possible damage. In addition, the slow dynamics of the droop-based power controller are desirable to decouple the power loop from the inner voltage and current regulation loops. This is the rule of thumb in control theory for the system that has nested control loops.[30,31,33,105–108] However, very slow power transients might threaten the DC link voltages and large circulating currents flow in cases of light loads.

8.2.2 | Power calculation

The LPF is used commonly in many works[46,100,109,110] to obtain the average power from single-phase instantaneous power measurement. In a balanced three-phase system, the instantaneous power equals the average power and such a filter might not be necessary. However, in an unbalanced three-phase system, the instantaneous power has a ripple component and a filter becomes essential to prevent the ripple component from propagating to the frequency and amplitude through the droop control feedback.[111] In addition, the slow response designed LPF decouples the power and voltage/currents loops which is essential for maintaining the systems stability. On the other side, this filter has a significant effect on the dynamics of the droop controller due to associated phase lag.[109]

Alternative methods are proposed in many studies[37,112] that have better dynamics, fast response, and smaller ripple. In addition, a comparison of many methods is investigated in Gao et al.[113] However, the speed of calculation might be slowed down to satisfy the nested loop system. Figure 8 depicts the response of LPF with different cut-off frequency ω_c with comparison against the integration filter used in Abusara et al.[37]

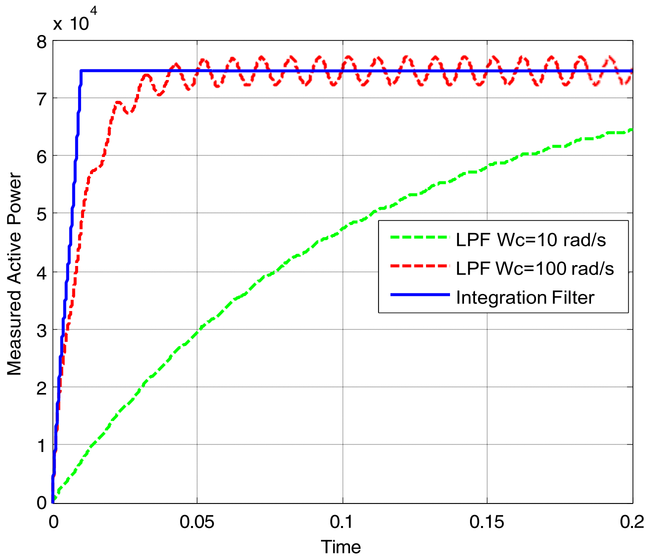

FIGURE 8 Average power measurement by: LPF ($\omega_c = 10$ rad/s), LPF ($\omega_c = 100$ rad/s), and integration filter. LPF, low-pass filter.

8.2.3 | Output impedance

Output impedance is quite essential for the proper operation of droop control. However, as mentioned earlier, the uncertainty of being pure inductive or resistive or in between has a negative impact on P and Q control decoupling. The nature of the output impedance is determined by the output filter, line impedance, and the control loop. In Abusara et al.,[111] the control loop gives an inductive output impedance while in Josep et al.[58] it is a resistive nature. The low voltage network has a resistive dominant impedance which has inherently good harmonic power-sharing capability and enhances the system damping.[63,70,114] However, inductive output impedance has a good capability of grid harmonic rejection.[37] Recently, the output impedance can be redesigned to have the desired behavior by the advantage of virtual impedance. The concept of virtual impedance has been widely used to overcome the problem of power coupling caused by high R/X ratio in low voltage distribution networks. It increases the inductive reactance/resistance of the inverter's output impedance without using additional physical inductors/resistors that would increase size and cost. Thus, it mitigates the effect of the network and line impedances on the droop control. Figure 9 illustrates how the nature of the output impedance can be redesigned by using the virtual impedance from inductive to resistive in (A) and from resistive to inductive in (B). The literature illustrates the recent researches toward developing the virtual output impedance. A parallel-connected virtual resistive impedance control method is proposed by Josep et al.[43] for current sharing in island mode. This gives the advantages of more damped system, in terms of resonance, and automatic harmonic sharing. In Guerrero et al.[65] an inductive virtual impedance is used. However, a concern for the virtual inductor control scheme is the inductor voltage drop calculation, which involves the differentiation of the line current. Differentiation can

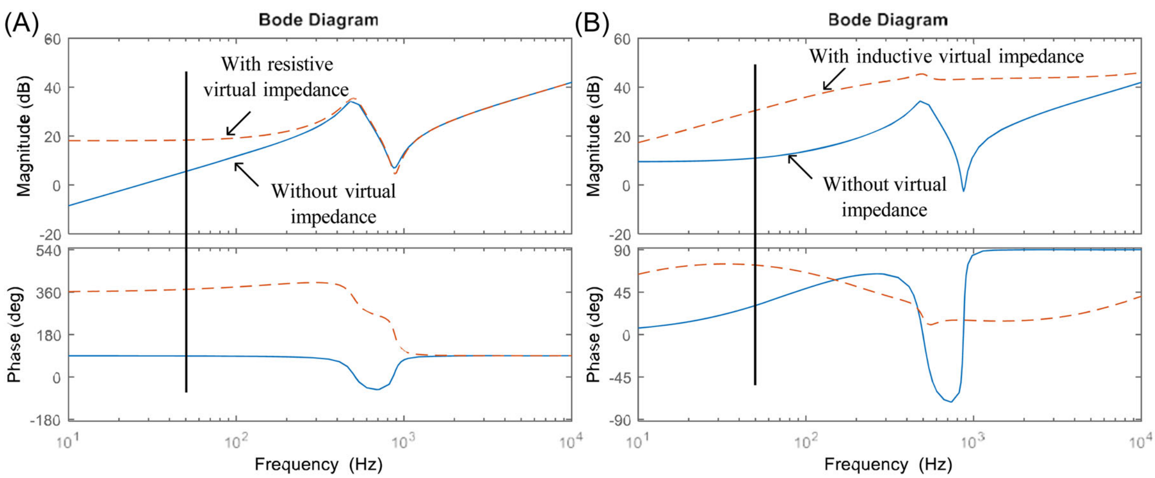

FIGURE 9 Output impedance different nature when it is redesigned by virtual impedance: (A) inductive output impedance redesigned as resistive and (B) resistive output impedance redesigned as inductive.

cause high-frequency noise amplification, which in turn may destabilize the inverter voltage control scheme especially during transient. A common approach to avoid noise amplification is to replace the differentiator with a high-pass filter (HPF) to attenuate the high-frequency gain of the resulting transfer function as in Yao et al.[115] The virtual impedance also supports the soft-start operation[46] by maintaining a high impedance at the beginning then reducing it to a nominal value at steady state, which minimizes the circulating current between the inverters. A realization of a capacitive output impedance has been discussed in Abusara et al.[116] to achieve accurate power sharing. It concludes that the capacitive output impedance improves the power quality compared with other impedances. Also, a universal droop control has been proposed in Zhong and Zeng[117] which dealt with parallel inverter with different types of output impedances as shown in Figure 10.

It is worth mentioning that some voltage/current controllers (resonant, predictive, and RC[77,116]) provide very high gain at the vicinity of the fundamental frequency and some harmonics to achieve zero steady-state error with good harmonics rejection/injection. These techniques also force the output impedance to be very low (ideally zero) and the use of the virtual impedance is the dominant factor to determine the output impedance behavior.[118]

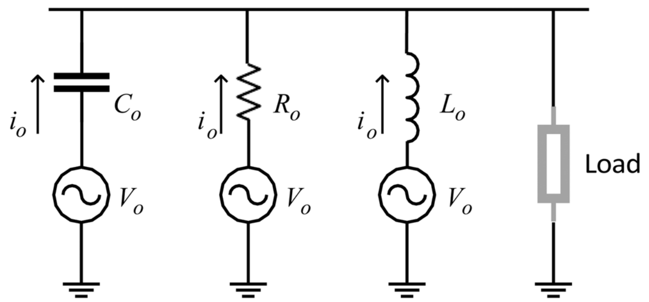

FIGURE 10 The considered microgrid setup in Zhong and Zeng[117] with different output impedances.

8.2.4 | Accurate steady-state power sharing

In grid-connected mode, the power control accuracy is achieved by the advantages of a PI controller[37,119] that eliminates the steady-state error of active and reactive power. However, this is difficult to be implemented in an island microgrid. The difficulty is generated by the trade-off between the accuracy of load sharing and the voltage/frequency regulation. If the droop gains are increased to obtain more accurate load sharing, this would degrade the regulation and may destabilize the system. Hyun-Koo Kang and Moon[120] proposed a droop control with two droop coefficients to maintain the stability in island mode during low and high loads. Wei Yao et al.[45] adopted a new droop control that makes the droop relation to be nonlinear between $P-\omega$ and $Q-V$ to decrease the drop of frequency and voltage during supplying heavy loads. In addition, an adaptive droop behavior against small and large loads steps is proposed in Haddadi et al.[121] A supplementary loop was proposed[122] to stabilize the system despite having high gains that are required for better load sharing. A decoupled control of virtual real and reactive power through frame transformation is proposed in De Brabandere et al.[123]

Other authors introduced many solutions as in Vásquez et al.[102] which used the second-order generalized integrator, that generates the filtered in-phase and quadrature-phase versions of the grid voltage/current, to estimate the grid impedance to substitute it in the droop control and strength the decoupling between active and reactive power.

Many strategies have been proposed to enhance a decentralized reactive power sharing. An algorithm has been proposed in Tuladhar et al.[124] which is based on additional control signal injection. The proposed solution injects signals with other frequencies (90 and 130 Hz) to send the information about the shared power between inverters through the same distribution lines. However, this could increase the control complexity and current distortion. Lee and Cheng.[47] proposed a method to compensate for the line impedance mismatches in which the reactive power is controlled in proportion to the voltage derivative. Although this method minimizes the reactive power-sharing error, it does not achieve equal sharing and it adds more complexity to the system. In Micallef et al.,[11] a centralized controller has been proposed to compensate for the voltage drop caused by droop controller and line impedances. However, the whole process is executed in the MGCC and all parameters are sent by a communication link and any loss in this link would lead to the traditional droop limitations. Li and Kao[119] proposed an online estimator of the voltage drop caused by the transmission lines to then refine the droop control gain to give an accurate Q sharing in island mode. However, the algorithm needs the inverters to operate in grid-connected mode initially to obtain a proper estimation to calculate the new droop gains. In addition, the controller complexity increases with the presence of local loads that affect the estimation process. In Zhong,[125] a novel controller that is robust against computational errors and component mismatches is proposed. The accuracy of the controller does not depend on the output impedance. It measures the load voltage continuously by a wired link and computes the difference between this measure and the local output voltage. This difference is an input to an integral controller to achieve accurate sharing of reactive power. However, this system only works accurately for local inverters near each other and local loads. For a far load point or large distances between the inverters, a wireless link could be used and any loss in this communication link even for a short period of time might lead to instability due to the existence of the integral controller. Furthermore, the controller does not take into account the cable's impedances that contribute to sharing inaccuracy if a local output voltage is fed back. He and Li[126] proposed a synchronized algorithm guiding all units to share the reactive power accurately by incorporating the measured reactive power in the frequency droop equation. However, this disturbs intentionally the active power-sharing accuracy. In addition, for any load variation after compensation, the accuracy of the sharing deteriorates and hence the algorithm needs to be executed again. Gao et al.[113] and Jinwei et al.[127] proposed an online estimation technique of the line impedance, using the harmonics of the line current and PCC voltage, to regulate the virtual impedance and enhance the reactive power-sharing accuracy. However, the controller complexity increases as well as the dependency on harmonics calculations which assume the existence of nonlinear loads during the estimation period.

8.2.5 | Sharing of current harmonics

Especially during supplying nonlinear loads in island mode, to cope with the nonlinear load sharing, in Josep et al.,[46] a method was proposed to share nonlinear loads by adjusting the output voltage bandwidth with the delivered harmonic power using a bank of band-pass filters. The latter extract the harmonic components from the current signal then reinject them into the grid. Resistive output impedance can be a good solution to share linear and nonlinear loads in applications such as uninterruptible power-supply systems.[128] In Skjellnes and Norum,[129] a novel fast control loop that adjusts the output impedance of the closed-loop inverters is used to ensure resistive behavior with the purpose to share the harmonic current content properly. Inductive output impedance seems to be the most natural output impedance.[46] However, it degrades the output voltage total harmonics distortion too much when supplying nonlinear loads due to the large impedance value seen by the current harmonics. A complex output impedance is presented in Yao et al.[115] that suggested a new design of a virtual output impedance composed of a virtual resistor with a virtual inductor associated with HPF. Eventually, it behaves like an inductor at nominal frequency and represents a resistive behavior against harmonics frequencies.

8.2.6 | Frequency and voltage regulation

In island mode, the PCC frequency and voltage do not match the set-points of the microgrid as it is subject to the droop control. Thus, a restoration and regulation process is required if the microgrid will be reconnected to the grid again. A secondary loop is proposed in many studies[66,130] adopting a PI controller to restore the required values. In Ritwik Majumder et al.[131] and Majumder et al.,[132] a phase droop control is used that makes the frequency independent of the load so it is fixed over the time. In addition, Sao and Lehn[133] allow the operator to tune the real power-sharing controller without compromising frequency regulation by adding an integral gain into the real power control.

8.2.7 | Hierarchal control

For developing a flexible microgrid, it is necessary to distribute the control tasks over levels. The latter decouples the control parameters and creates a management system for frequency and voltage restoration, reactive power compensation, mode transfer, and power dispatch optimization. The following is the hierarchical control, Figure 11, required for an AC microgrid proposed in Guerrero et al.[66]:

1. Primary control based on the droop method to allow the connection of different AC sources in parallel and to share the load wirelessly. In addition, it is responsible for the voltage and current regulation in terms of a particular reference.
2. Secondary control avoids the amplitude and frequency deviation produced by the primary control. Only low-bandwidth communications are needed to perform this control level. A synchronization loop can be added at this level to transfer from islanding to grid-connected modes.
3. Tertiary control allows importing/exporting active and reactive power to the grid, estimates the grid impedance and nonplanned islanding detection.[134]

Guerrero et al.[66] proposed a PI controller to implement the secondary and tertiary control after sensing the voltage, current, and frequency at both sides of STS and sending them by low-bandwidth communication.

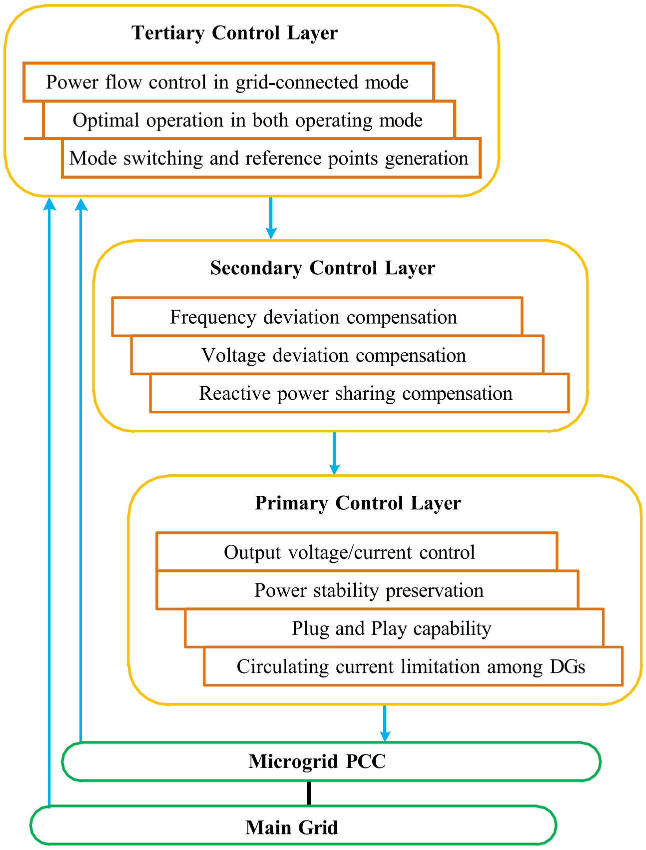

FIGURE 11 Hierarchical control layer of a microgrid. DG, distributed generation; PCC, Point of common coupling.

By this sort of level distribution a seamless mode transition is achieved to reduce the initial circulating currents. Other works are proposed in many studies[9,37,135] for the sake of managing these tasks automatically as well.

8.3 | Power management between RES and ESS

The intermittent nature of power supplied from the RES generation makes the ESS an indispensable component to keep the power balance between generation and consumption.[136] In island microgrid comprised of the ESS and RES generation, the ESS unit usually operates as a grid-forming unit that regulates the AC bus, while the RES works as grid-feeding units that inject all available power into the system.[137] Therefore, coordinating power management is required to ensure efficient utilization of renewable energy, while keeping the ESS from overcharge and overdischarge conditions.

Bus-signaling method, by using different bus voltage/frequency thresholds to trigger mode-changing actions for the DGs and the ESS coordination is proposed in Boroyevich et al.[138] and Dan et al.[139] However, when the number of DGs increases, it becomes difficult to determine the bus voltage/frequency thresholds. A modified droop method is presented in Gomes de Matos et al.,[140] which takes into account both state of charge (SOC), and available power in the ESS and RESs, respectively. Nevertheless, the switching actions of droop curves may trigger stability problems induced by sudden bus frequency changes in microgrids. An interesting autonomous active power control strategy is proposed in Wu et al.[141] for island microgrids to achieve power management in a decentralized manner. The proposed control algorithm is based on the frequency bus-signaling of ESS and uses only local measurements for power distribution among microgrid elements. The PV system senses the frequency and adapts the output power accordingly as in Figure 12. A multisegment adaptive droop control is presented in Mahmood et al.[142] to provide independent deployment of PV and battery units in an island microgrid. Wu et al.[143] proposed a smooth switching droop control applied to RES/ESS units for their coordinated operation in island microgrids, Figure 13, which combines the advantages of both droop control and bus-signaling methods.

Integrating ESS in a microgrid could be in an aggregated or distributed manner. For the distributed ESS, a coordination method is required to ensure ESS balance to avoid deep-discharging in one unit and overcharging in others. In addition, according to the algorithm proposed by Tan et al.,[145] the battery and the fuel cell are used to share the deficit load using droop control when the power supplied from the PV and the microturbine is insufficient. This could deplete the battery storage, which is the most critical element in the operation of the island microgrid, and may result in shutting down the microgrid. Instead of sharing power, the battery storage is commonly used to supply/absorb power during transients,[146] and to supply the deficit power only after all other energy sources reach their ratings. In Kim et al.,[146] a central EMS is employed to coordinate the dispatchable units so that the battery neither supplies nor absorbs any power at a steady state. A microgrid composed of a PV unit and a separate battery storage unit is considered in Serban and Serban.[147] A control strategy is proposed to avoid overcharging the battery without relying on communication. According to this strategy, once the battery voltage exceeds its maximum limit while being charged, the battery converter decreases the line frequency below the anti-islanding limit of the PV VCS. Consequently, the PV unit is disconnected leaving the battery to supply the load demand in the microgrid.

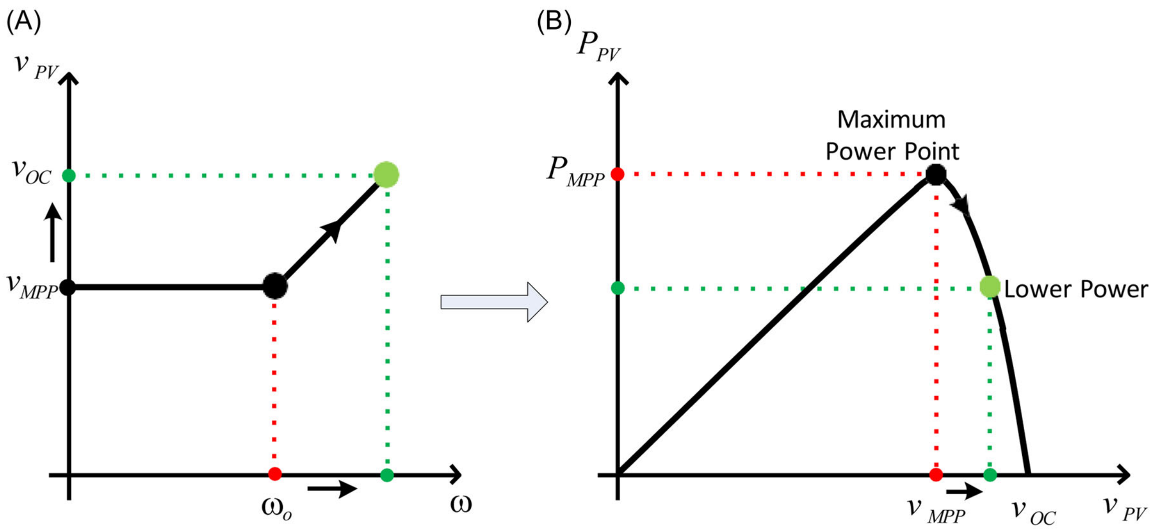

FIGURE 12 (A, B) Autonomous proposed power management between ESS and PV in Dan et al.[144] for PV power curtailment. ESS, energy storage system; MPP, maximum power point; PV, photovoltaic.

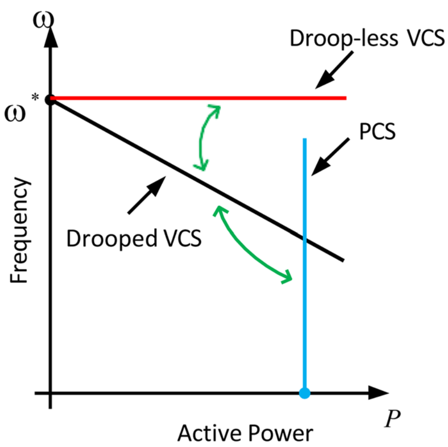

FIGURE 13 Droop control switching proposed in Wu et al.[143] for power management between ESS and RES. ESS, energy storage system; PCS, power-controlled source; RES, renewable energy source; VCS, voltage-controlled source.

This could result in power flow chattering, especially if the battery unit cannot support the whole load demand.[148] A fuzzy system is proposed by Diaz et al.[149] to adjust the droop gains in accordance with the SoC at each ESS to achieve the balance between the storage units.

8.4 | Modeling

It is necessary to build the stability margins of a microgrid and analyze the controller's functions against the uncertainties in the system. In grid-connected mode, each unit could be dealt as a single unit as the grid stiffness decouples the interaction between the inverters. However, in island mode, the dynamics of each inverter is affected by other inverters. The commonly used method to build a microgrid model is the small signal technique. In many studies,[37,100,109] a grid-connected inverter model is developed and the responses have been analyzed and compared to practical setup results, while in Xinchun et al.,[110] two island inverters are modeled to investigate the droop gains stability margins. Pogaku et al.[150] have presented a systematic approach using the Parks d–q transformation to model an inverter-based microgrid containing multi-inverters, including network and loads elements. Rasheduzzaman et al.[151] used the same model but added PLL states for more accurate results especially when calculating the steady-state values of the reactive power. Another model was developed in Kahrobaeian and Ibrahim Mohamed[152] for multi-island inverters in the *abc* frame and it was used to evaluate the effect of communication time delay on system stability. Similarly, Kulkarni and Gaonkar[153] a robust control strategy pooling an improved droop with a virtual impedance control-based droop control for power sharing with f/V restoration is proposed. However, in all these models, the DC link voltage state of each inverter has not been included. The DC link voltage was included in the small signal model reported by Issa et al.[16] but the model was for two parallel inverters only. In Pogaku et al.,[150] the inner voltage and current controller loops were included in the model but it was concluded that the outer power-sharing loop dominates the effect on stability. In addition, Iyer et al.[154] assumed that the dynamics of the inner voltage and current loops can be neglected as their bandwidths are much higher than the outer droop controller loop due to the LPF used to average the active and reactive powers. A simplified model including the states of the DC link voltages was developed by Issa et al.[51] to focus on the low-frequency stability modes as in Figure 14. Models containing different RES and ESS are developed in many studies[148,155–157] for controller design purposes which have been verified by Matlab/Simulink and practical implementation.

9 | PROSPECTIVE TRENDS

It is seen that the droop-based power management strategies are the most interesting techniques among other techniques. Most of the research outcomes tried to overcome the limitations of the droop control and to contribute to the development of it to produce a more robust and reliable controller. The abovementioned microgrid control schemes, challenges, and potential solutions have been summarized in Table 5. This serves toward presenting this technique to the industry which produces reliable products for the community. The majority of droop control

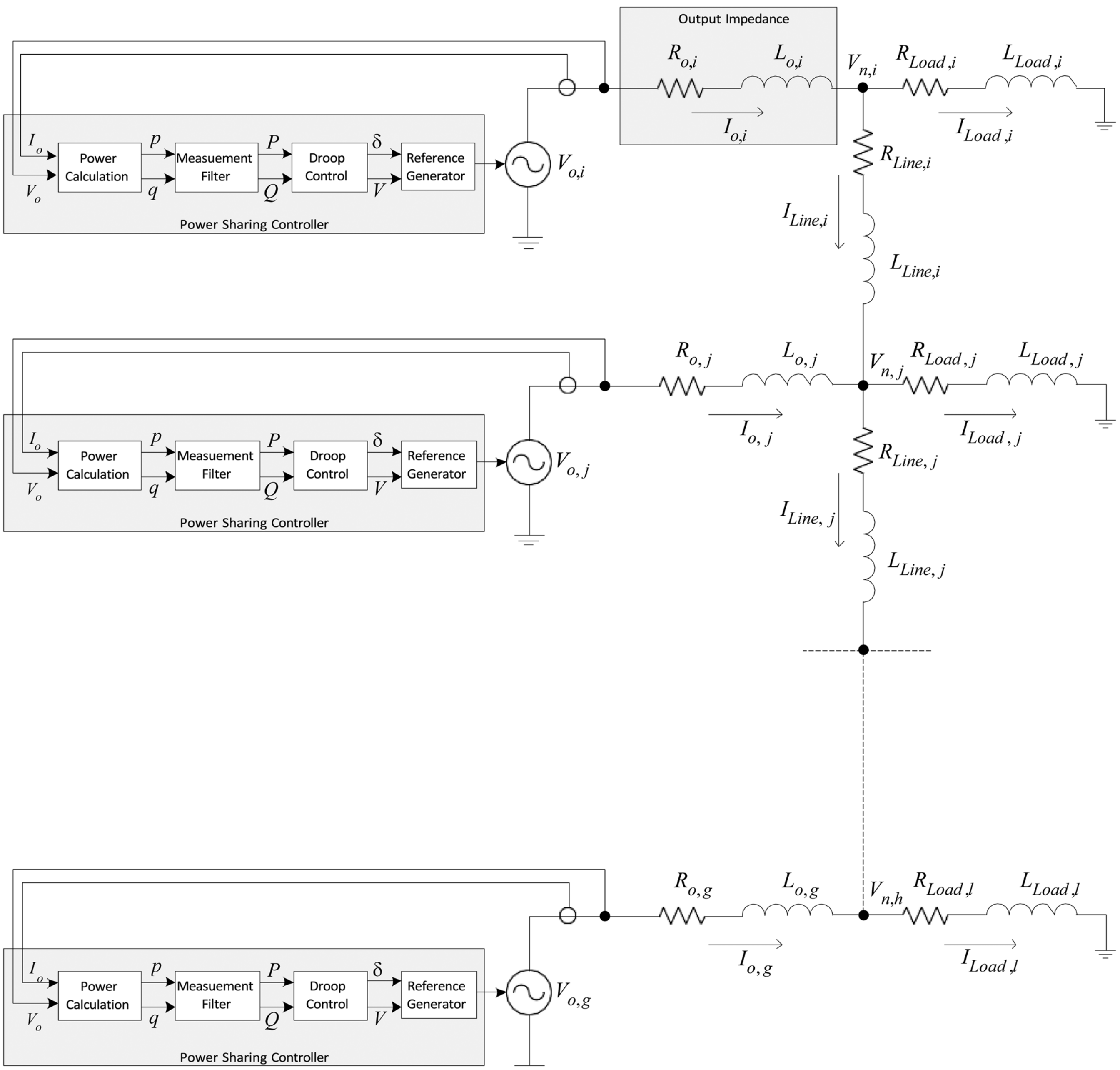

FIGURE 14 Simplified multi-inverter island microgrid.[51]

TABLE 5 Microgrid control schemes, challenges, and potential solutions.

Control objective	Challenges	References	Proposed solution
Robust voltage/current regulation	– During load variation	[76, 96]	– Different controllers: PI, PR, RC, predictive, deadbeat
	– Filter resonance generation	[75, 97]	– Passive and active resonance damping
	– Interaction with other units	[37, 98, 99]	– Extra loops for resonance compensation – Design recommendation for voltage loop bandwidth
	– Power-sharing dynamics	[65, 122] [100]	– Improved droop control using proportional–integral–derivative control and extra-phase loops
		[45]	
		[101]	– Adaptive droop control
		[103]	
Accurate output power control/sharing		[37, 112]	– Other power calculation methods
	– Output impedance nature	[43, 65]	
		[46, 115]	– Virtual output impedance
		[158]	
	– Current harmonics sharing	[128, 129]	– Resistive virtual output impedance
	– Reactive power-sharing inaccuracy	[11, 95, 119, 125]	– Communication-based secondary control level
	– Unintentional islanding	[16]	– Extra DC link voltage loop
Supervisory control	– Voltage and frequency restoration – Seamless mode transfer	[9, 37, 66, 130, 135]	– Hierarchical control levels
	– Optimized power flow	[137–144, 146–149, 159, 160]	– AC bus-signaling-based master–slave operation
Modeling	– Dynamics prediction and stability assessment	[100, 37, 109, 150–157]	– Transient evaluation by full and simplified models – Optimized power steady-state distribution of RES

Abbreviations: AC, Alternating Current; DC, Direct Current; PI, proportional integral; PR, proportional resonant; RC, repetitive control; RES, renewable energy source.

enhancement contributions use low-bandwidth communication. It is highly recommended to use such a link as it will be available for supervisory and management purposes instead of using costly high bandwidth links. Consequently, the prospective trends should highlight reliable low-cost solutions for communication between each DG and MGCC. In addition, more studies have to assess the stability of microgrids and their immunity against the speed of communication and the loss of it.

The literature covered the grid-connected mode and the island mode modeling for multi-inverter units. However, it is the lake of modeling of different controlled units within a microgrid and how the modes of stability are affected by each one. Some of the DGs could work as PCS and others as VCS. Some units have different output impedance and the droop control rules are different in each. Also the frequency and angle droop control in the same microgrid has not been addressed. The variety of loads (constant power and constant current constant voltage) also must be included in the model. Furthermore, the modeling of multi-inverters connected to a weak grid with high impedance is important. These cases reflect the future community microgrids which the research aims to improve.

Another research trend is about the efficiency of the converters and how to get the advantage of each power source efficiently regardless of the voltage and current levels and the conditions of generation like Concentrated Photovoltaic system and how the current MPPT technique will work.

10 | CONCLUSION

This paper has provided a comprehensive overview of the operation modes and control strategies for DG units within microgrids, with a particular emphasis on grid-connected and island modes. Through our review, we have explored a range of control schemes at different levels, highlighting their applications and effectiveness in various scenarios. We have identified and discussed several key challenges faced by microgrids, including accurate power control and sharing, voltage and frequency regulation, effective power management among DG units, integration of RESs, and seamless transition between operation modes. These challenges are critical to the development of a flexible and smart distributed power system, and addressing them is essential for the advancement of microgrid technologies. In response to these challenges, the paper has presented potential solutions proposed in the literature. These solutions encompass advanced control strategies, innovative technological approaches, and practical implementation techniques. We have emphasized the importance of droop control as a pivotal strategy in managing the dynamic and decentralized nature of microgrids, especially in islanded operations where the stability and reliability of power supply are paramount.

Furthermore, we have highlighted the practical aspects of implementing these control strategies in real-world scenarios. The discussion on the practical challenges and considerations in implementing droop control in microgrids provides valuable insights into the gap between theoretical research and practical application. This gap represents an opportunity for future research and development in the field.

As microgrid technologies continue to evolve, the integration of RESs and the development of more efficient and robust control mechanisms remain key areas for ongoing research. The future of microgrids looks promising, with advancements in control strategies and technologies paving the way for more sustainable, reliable, and efficient power systems.

In conclusion, this paper contributes to the body of knowledge by not only reviewing the current state of microgrid control strategies but also by identifying future directions and challenges. It serves as a resource for researchers and practitioners in the field, offering a foundation for further exploration and innovation in microgrid technologies.

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