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Primary control in AC microgrid

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Abstract Microgrids (MGs) are a transformative development in modern power systems, enabling the integration of Distributed Generation (DG) units and Renewable Energy Sources (RESs) into localized energy networks. DG unit's interface with the main grid through power electronics-based converters, which pose significant challenges in both steady-state and dynamic operation. This paper highlights the importance of primary control in MGs, which ensures key functions such as real-time power sharing, voltage and frequency regulation, and stability. In this study, traditional primary control methods are categorized into communication-dependent, communication-independent, and enhanced droop control techniques. While these methods are effective under steady-state conditions, they often rely on linear models and lack the responsiveness needed for fast-changing dynamics, leading to degraded performance during transient conditions. To address this, adaptive droop controllers that modify parameters in real time are explored for improved dynamic response and system stability. Further, traditional controllers struggle with handling nonlinearities and system uncertainties. To overcome this, robust nonlinear control strategies such as Sliding Mode Control (SMC), H∞ control, and backstepping are analyzed. These methods improve performance but depend heavily on accurate system modeling and predefined uncertainty bounds, limiting their practical deployment. To meet the growing complexity of MGs, this study explores Artificial Intelligence (AI)-based control strategies, including fuzzy logic (FL), machine learning (ML), and optimization techniques. These intelligent controllers offer self-adaptive capabilities, allowing real-time learning and adjustment to changing conditions, thereby enhancing system resilience, fault handling, and performance. This review presents a structured comparison of conventional, robust, and AI-based primary control methods, outlining their respective advantages, limitations, and the potential for hybrid solutions. It provides a comprehensive overview that supports the development of more intelligent and responsive MG control systems.

Keywords: microgrid, AC microgrid, hierarchical control, traditional droop control, robust and adaptive control, artificial intelligence-based control

1. Introduction

Microgrid (MG) represents a key advancement in modern power systems. It integrates distributed generation (DG) units, renewable energy systems (RESs), energy storage systems (ESSs), and controllable loads into a unified, localized network. As the world moves toward more sustainable and decentralized energy systems, MGs have emerged as a critical solution for enhancing robustness of power systems. This paradigm shift addresses the pressing challenges posed by the increasing penetration of variable RES. It also ensures stable operation across diverse operating conditions.

The versatility of MGs lies in their ability to operate seamlessly in both grid-connected and islanded modes (Katiraei & Iravani, 2006; Piagi & Lasseter, 2006; Zeng et al., 2011). In grid-connected mode, MGs synchronize with the utility grid, allowing for energy exchange and ancillary services such as frequency regulation and voltage support. On the other hand, in islanded mode, MGs operate autonomously, supplying power to local loads even in the absence of grid support. This dual-mode functionality, and the need to maintain stable operation in both modes, present significant technical challenges in MG control (Li et al., 2022).

These challenges include voltage and frequency regulation for different operating modes, effective load sharing, and coordination of DG units, resynchronization with the main grid, and optimizing power flow and operating costs. These tasks vary in importance and timescale, necessitating a hierarchical control structure to address each need at its respective control level (Lasseter, n.d.; Olivares et al., 2014). It provides a structured approach that enables effective management of decentralized and complex MG systems. Hierarchical control strategies for MGs consists of three levels: primary**,** secondary**,** and tertiary control (Guerrero et al., 2011) as shown in Figure 1. The flow of information and control signals between the three control levels i.e., primary, secondary and tertiary level is indicated by arrows, where tertiary control can influence secondary control, which in turn can adjust primary control parameters. The primary control directly interacts with the interfacing inverter, managing its immediate responses to grid conditions.

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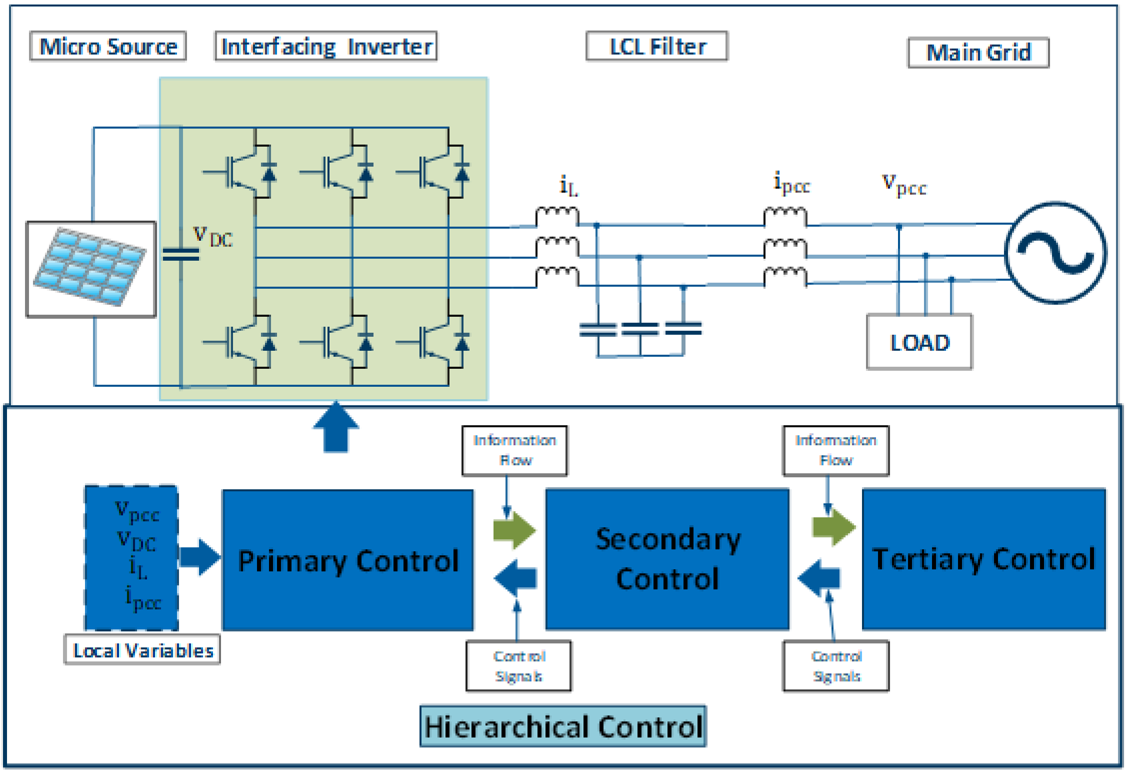

Figure 1 Hierarchical control framework. *Source:* Smart Hybrid AC/DC Microgrids, (n.d.).

Each level operates on distinct timescales and focuses on specific objectives. Figure 2 depicts the tiered nature of the control systems, from primary to tertiary, and their respective functions and operational time scales within a MG context.

Energy management in MGs is carried out at the tertiary control level, which operates at the highest tier of the hierarchical structure. This level focuses on optimizing operational efficiency, reducing costs, and enhancing system reliability by considering various power generation technologies and their respective capacities (Marín et al., 2019; Razmi & Lu, 2022) . At this stage, optimal setpoints are established based on the requirements of the main power grid, such as providing voltage stabilization, frequency support, or other ancillary services (Moradi et al., 2014).

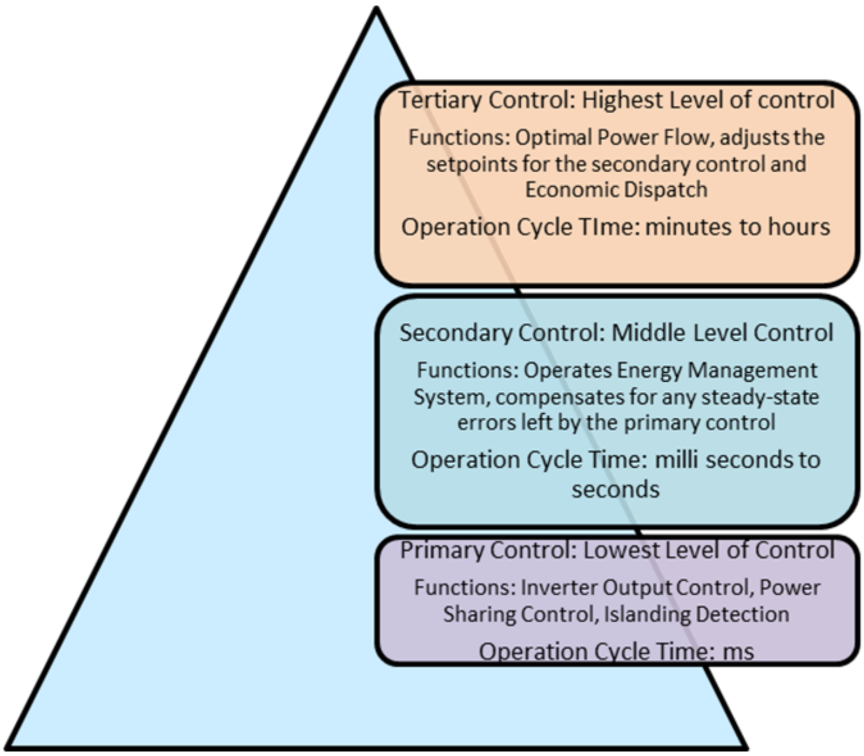

Figure 2 Function and timescales of MG hierarchical control levels.

Additionally, the tertiary control level plays a key role in coordinating the operation of multiple interconnected MGs, ensuring seamless interaction and collaboration within the system (Jadav et al., 2017). At the opposite end of the hierarchy lies primary control, which forms the foundational layer (Hu et al., 2021). Its primary responsibilities include managing critical parameters such as voltage and frequency, ensuring stable operation, and regulating power-sharing and injection among DG units (Hu et al., 2022; Monica & Kowsalya, 2016; Olivares, Mehrizi-Sani, Etemadi, Cañizares, et al., 2014). Between these two levels is the secondary control layer, which acts to improve power quality by addressing deviations introduced by the primary control. It works to restore voltage and frequency to their nominal values while maintaining accurate power-sharing among units (Jangid et al., 2024). This layered control framework ensures an efficient and reliable management system for MGs, addressing both local and system-wide challenges effectively.

There have been several reviews on primary control layer focusing on specific methods of MG control such as droop control (Ahmed et al., 2021; Gupta et al., 2018; Hu et al., 2022; Sahoo et al., 2018; Tayab et al., 2017), Robust control (Asadiet al., 2022; Hu et al., 2021; Panda & Subudhi, 2023a; Mohammadi et al., 2022), (Panda & Subudhi, 2023b) or AI based control (Mohammadi et al., 2022; Trivedi & Khadem, 2022). A systematic review covering the full spectrum of primary control strategies including conventional, robust and AI based controllers is missing. This paper aims to bridge the gap by providing a comprehensive review including all the conventional and advanced primary level control techniques in AC MGs.

This work builds upon our previous study (Diwan & Linus, 2024), which focused on droop-based control methods. In this paper, the foundational concepts from that study have been expanded to include a broader spectrum of primary control strategies, with the addition of robust and AI-based approaches to provide a more comprehensive perspective.

The literature for this review was gathered through searches in IEEE Xplore, ScienceDirect, and Google Scholar, using keywords such as 'microgrid primary control', 'droop control microgrid', 'robust control microgrid', and 'AI microgrid control'. We focused on articles from the last ~10 years (2013–2024) for recent techniques. We also included seminal works for foundational methods. More than 100 publications were selected for detailed analysis, including journal papers, conference proceedings, and review articles. Priority was given to high-impact and highly cited works to ensure coverage of influential contributions.

1.1. Research gaps and contributions of the article

1. This article systematically categorizes the primary level control methods used for power sharing, voltage regulation, and frequency control in MG as shown in Figure 3. The categorization of conventional controllers is based on their reliance on communication: communication-dependent approaches, which require inter-device communication, and communication-independent methods, which operate without such links. The classical control techniques are discussed in detail and the advantages and disadvantages of these methods are clarified. Modified droop control strategies, which address specific limitations of classical controllers are also briefly discussed outlining their advantages and disadvantages. Promising techniques like virtual synchronous machine (VSM) and impedance shaping are also discussed in depth.

2. Traditional controllers assume that the system operates around a steady state and rely on simplifying assumptions. They fail to deliver a fast and accurate dynamic response during transient conditions or sudden changes in operating parameters. This limitation underscores the need for advanced control systems capable of rapid adaptation and precise performance under dynamic conditions. This review explores several adaptive droop controllers that offer several benefits, such as fast dynamic response [56] and performance remaining unaffected by system impedance.

3. Conventional control methods rely on linear system models and assume steady-state conditions, making them ineffective in handling system uncertainties, nonlinear dynamics, and transient disturbances. These limitations result in sluggish dynamic response and difficulty in ensuring stable operation under variable loads and generation conditions (Asadi et al., 2022; Hu et al., 2021; Kumar Panda & Subudhi, 2023a; Mohammadi et al., 2022). To address these shortcomings, the article explores robust nonlinear control techniques such as Sliding Mode Control (SMC), H∞ control, and backstepping control. These controllers enhance system resilience and improve performance under uncertain and rapidly changing MG conditions.

4. While robust control techniques improve stability and dynamic performance, they often rely on predefined system models, requiring precise mathematical representations of uncertainties and disturbances. This dependency makes them less adaptive to real-time changes and complex MG environments where system parameters fluctuate unpredictably. Furthermore, robust controllers generally involve complex tuning processes and high computational costs, limiting their scalability in large-scale MG applications (Mohammadi et al., 2022; Trivedi & Khadem, 2022). To overcome these challenges, AI-based methods such as ML, FL and optimization controllers provide an intelligent alternative by eliminating the need for explicit mathematical modelling. AI-driven controllers can learn from real-time operational data, adapt autonomously to changing grid conditions, and optimize MG performance with minimal manual intervention. This study highlights the growing role of AI in MG control, showcasing its ability to enhance system efficiency, flexibility, and resilience in modern energy networks.

The rest of the article is organized as follows:

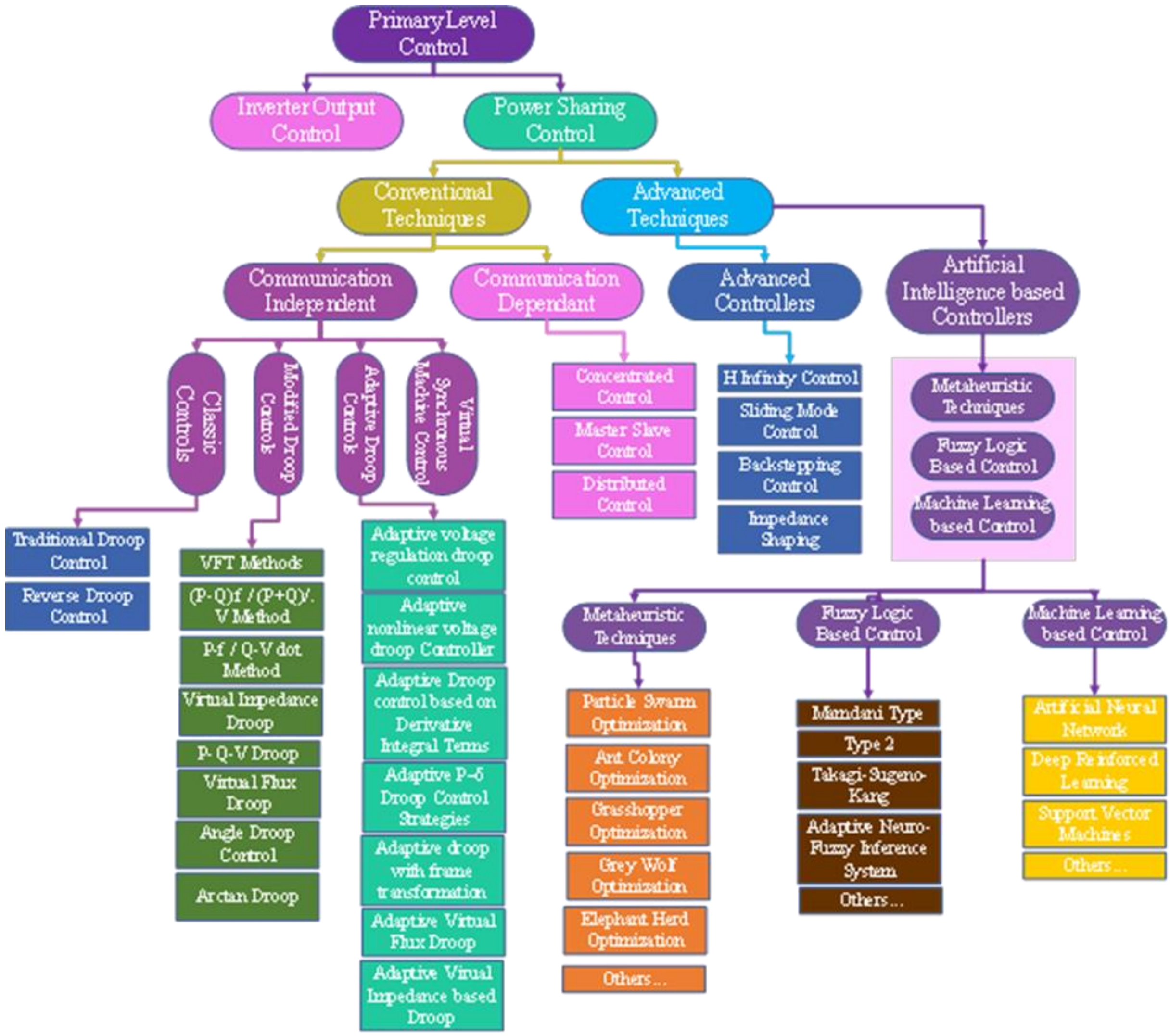

Figure 3 Categorization of PSC methods at the primary level of hierarchy.

Section 2 discusses the operating modes of MGs, i.e., grid-connected, islanded, and transitional states, and highlights their features, benefits, and challenges. Section 3 explores local primary control mechanisms for MGs, focusing on inverter output control, power-sharing, and classification of control techniques such as communication-dependent and independent methods. It also discusses traditional droop control methods and their limitations, followed by advanced droop techniques to address specific challenges. It includes virtual synchronous machine (VSM) control, which simulates the rotational inertia of traditional generators via control algorithms and stabilizes the frequency changes. Additionally, it focuses on adaptive control strategies, an evolution of traditional droop methods, aiming to address their limitations by dynamically adjusting control parameters on the basis of real-time operating conditions. Section 4 introduces robust nonlinear methods such as $H\infty$ control, sliding mode control, backstepping, and impedance shaping for enhanced MG management. Section 5 emphasizes the transformative role of AI in MG operations and management. This highlights the application of AI techniques to address challenges posed by the integration of renewable energy sources, dynamic load demands, and system uncertainties. Section 6 discusses future trends, and Section 7 concludes the article.

2. Modes of Operation

The IEEE 1547.4--2011 Guide delineates four distinct operational modes, each serving a unique purpose within MG systems. These modes encompass normal parallel, where the MG is seamlessly integrated with the grid. There is also the island mode, which represents self-sufficient, isolated operation. Additionally, we have the transition-to-island mode, which orchestrates the shift from grid-connected to islanded operation, and the reconnection mode, facilitating the return from islanded to grid-connected operation.

To ensure the smooth standardization of these islanding, reconnection, and transitional processes, strict adherence to the IEEE 1547 standard guidelines is paramount within MG control systems (Institute of Electrical and Electronics Engineers & IEEE-SA Standards Board., 2011).

An MG, as a versatile energy system, can operate in two primary modes: grid-tied and stand-alone (Katiraei & Iravani, 2006; Piagi & Lasseter, 2006; Zeng et al., 2011), as illustrated in Figure 4. Furthermore, it possesses the inherent capability to seamlessly navigate the transitions between these two modes, as documented in the literature (Institute of Electrical and Electronics Engineers. & IEEE-SA Standards Board., 2011; Karimi et al., 2008; Lasseter, n.d.; LI & NEJABATKHAH, 2014; Nikkhajoei & Lasseter, 2009a). To maximize its advantages, it is highly advisable for the MG to function effectively in both modes.

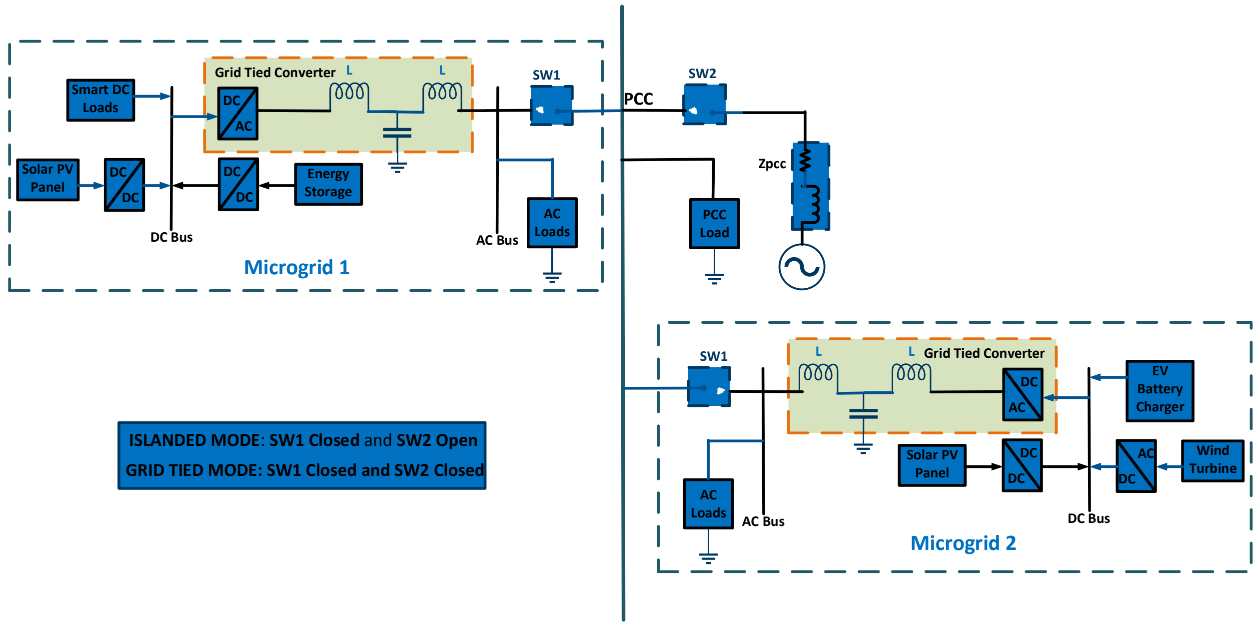

Figure 4 Islanding and Grid-Tied modes of MG operation.

2.1. Islanded/standalone mode

Islanding is the disconnection of the MG from the host grid. It can be either scheduled or unscheduled.

Scheduled islanding can occur in situations such as planned maintenance or when the degraded power quality of the host grid can endanger MG operation (Olivares et al., 2014). Unscheduled islanding can occur due to faults and other unplanned events that are unknown to the MG (Olivares et al., 2014).

In island mode, the electrical energy needed for local loads is provided primarily by internal DG sources and their power converters. To ensure the proper functioning of an MG and prevent issues related to stability, power quality, and long-term operation, it is necessary to internally generate voltage and frequency references. This objective is achieved through the use of grid-forming units. Consequently, it becomes necessary for at least one of the DG sources, along with their power electronics interfaces, to be part of this group to facilitate this internal reference generation.

The island mode offers the innovative advantage of operating independently from traditional grids, benefiting remote areas and enhancing experiences for those already connected to established power systems. This results in more reliable, flexible, and intelligent engagement with electricity.

However, several challenges are observed in islanding operations.

1. Low-inertia impact on reliability: The reliability of an MG is susceptible to its low-inertia characteristic, which may lead to an outage in situations of insufficient power generation or a sudden surge in demand (Lasseter, n.d.; Nikkhajoei & Lasseter, 2009a).

2. Voltage Quality Control for Critical Loads: In islanded mode, when critical loads are connected to the MG, it becomes imperative to ensure voltage quality control. This control mechanism should effectively maintain low levels of total harmonic distortion (THD) across a range of load scenarios.

In islanded mode, an energy storage unit plays a role akin to the inertia of a synchronous generator, mitigating temporary imbalances between power generation and demand (Olivares et al., 2014). As a result, system stability can be improved through voltage/frequency control in a droop-based configuration (Olivares et al., 2014; Tang & Qi, 2012).

The control techniques for the islanded mode of an MG can be either communication-based or without communication and can be droop-based or droop-independent. Nevertheless, opting for a control method that does not depend on communication proves to be both cost-effective and dependable for practical operation.

2.1.1. Grid-connected or grid-t tied mode

In the grid-connected mode, the MG controller ensures that the power flows from the MG to the utility main grid if the generated power of the DG units is in excess and can provide ancillary services. However, it also imports power from the main grid when the generated power is less than the local demand (Olivares et al., 2014).

In this mode, the main grid supplies voltage and frequency references to the converters in the DG units within the MG. The interfacing converters function in current control mode, regulating the flow of real and reactive power into the grid according to the required parameters (Rocabert et al., 2012).

This control strategy can employ various reference frames, such as natural, stationary, or synchronous frames. Synchronization between the MG and the main grid is achieved via mechanisms such as the phase-locked loop (PLL) or frequency-locked loop (FLL), along with their associated reference structures (Rodriguez et al., 2011).

The grid-connected mode plays a critical role in ensuring the stability and reliability of the power system by dynamically balancing the energy flow between the MG and the utility grid. This enables the MG to function seamlessly as part of the larger grid infrastructure, contributing to improved energy efficiency and resource utilization. By using advanced control techniques, such as droop control and coordinated converter operation, the system ensures that the voltage, frequency, and power quality parameters remain within acceptable limits, even under fluctuating load and generation conditions. This mode also enhances the resilience of the power system by integrating renewable energy sources, reducing dependence on conventional generation methods, and enabling effective demand-side management.

3. Primary Control

It is often referred to as local or internal control, is the first level in the control hierarchy and is characterized by its rapid response. This level of control relies solely on local observations without the need for any external communication. It encompasses the actions taken by local controllers located at the terminals of converters interfacing with the grid or load.

Since primary control has a faster response than other control levels do, it detects islanding, distributes power, manages output, and switches between controller modes accordingly (Karimi et al., 2008; Katiraei et al., 2004; Yazdanian & Mehrizi-Sani, 2014). The primary goals of this control system are met by ensuring that the DG units share active and reactive power accurately. This involves the use of power controllers.

Additionally, it involves keeping the voltage at the terminal of the voltage source converter (VSC) steady and maintaining the frequency with voltage controllers.

Furthermore, achieving the current necessary for filter inductors is accomplished by employing current controllers. Therefore, it offers control over the voltage and current output of the converter, along with the power distribution, via both centralized and decentralized methods. The primary control has bandwidths of 5 kHz and 20 kHz for current control and voltage control and time scales on the order of milli-seconds.

The fundamental control hardware in the primary level of control is the outer loop of voltage control and the inner current loops of DERs.

Current controllers are generally classified into two types: linear and nonlinear. Linear controllers include methods such as PI controllers in a synchronously rotating reference frame, state feedback, PR controllers in a stationary reference frame, predictive controllers, and deadbeat controllers. PI controllers are primarily used for tracking DC commands because of their ability to address steady-state errors, whereas PR controllers are better suited for tracking AC commands.

In contrast, nonlinear controllers involve techniques such as hysteresis control, sliding-mode methods, delta modulation, optimization-based approaches, neural networks, and fuzzy logic controllers. The key aspects of primary control include managing inverter output and implementing power-sharing mechanisms, which are elaborated upon in subsequent sections.

3.1. Inverter output control

Control strategies for the grid-side converter are predominantly based on two intertwined control loops. A rapid internal current control loop is tasked with regulating the grid current, focusing on power quality and current protection, which includes harmonic compensation and a dynamic response. In contrast, an external voltage control loop is utilized to manage the DC-link voltage, aiming to balance the power flow within the system (Agirman & Blasko, 2003; Saccomando & Svensson, 2001; Song et al., 2003; Teodorescu et al., 2004; Teodorescu & Blaabjerg, 2004; Zhu et al., 2003). The voltage controller is specifically designed to ensure system stability, albeit with slower dynamics.

Some approaches have taken a different route by employing a dc-link voltage control loop integrated with an inner power control loop, thereby indirectly managing the current fed into the utility grid (Ramos et al., 2002). Additionally, there are strategies that utilize an outer power control loop paired with an inner current control loop (Candusso et al., 2002).

This discussion also categorizes control strategies on the basis of the reference frames in which they are implemented, highlighting the distinctive features of each configuration.

In the realm of MG dynamic response and stability, multivariable control techniques have been introduced (Bahrani et al., 2013; Karimi et al., 2010) to counteract the uncertainties caused by nonlinear loads and variable load parameters. These studies have focused on the voltage control of MGs comprising a single DG unit and an attached RLC load, where the load parameters either vary around their standard values or are within a predefined limit.

3.2. Power sharing control (PSC)

The PSC is part of the primary control level in the hierarchical control levels of the MG. Power sharing control mechanisms are fundamental for the effective management of MGs; ensuring the reliability, stability, and economic operation of power systems; and maximizing the use of RESs.

At the heart of PSC algorithms, inverters serve as key components responsible for interfacing various DERs, such as solar photovoltaic (PV) panels, wind turbines, and battery storage systems, with the MG infrastructure (Lasseter & Paigi, 2004). Renewable and micro energy sources often generate DC or nonutility-grade AC (Li & Nejabatkhah, 2014).

The primary role of inverters entails converting the direct current (DC) output of these sources into an alternating current (AC) suitable for both consumption within the MG and possible exportation to the main grid (Li & Nejabatkhah, 2014). By adjusting the power output of the DER, inverters can help manage and balance the loads within the MG, ensuring that the supply meets demand efficiently.

The control techniques of MGs can be classified as communication-based or without communication and as droop-based or droop-independent. The classification of these strategies is shown in Figure 5. The communication-based droop-independent PSC strategies for DG units include concentrated control (Shanxu et al., 1999; Prodanovic, 2000; Siri et al., 1992b; Vandoorn et al., 2013a;Wu et al., n.d.), master/slave control (Jiann-FuhChen & Ching-Lung Chu, n.d.; Petruzziello et al., n.d.-a; Siri et al., 1992a; Yunqing Pei et al., n.d.-a), and distributed control (Jingtao Tan et al., n.d.; Sun et al., 2003). On the other hand, control strategies without communication are based on the droop concept (Chen et al., 2019; Lee et al., 2013; Olivares et al., 2014; Zhong, 2013).

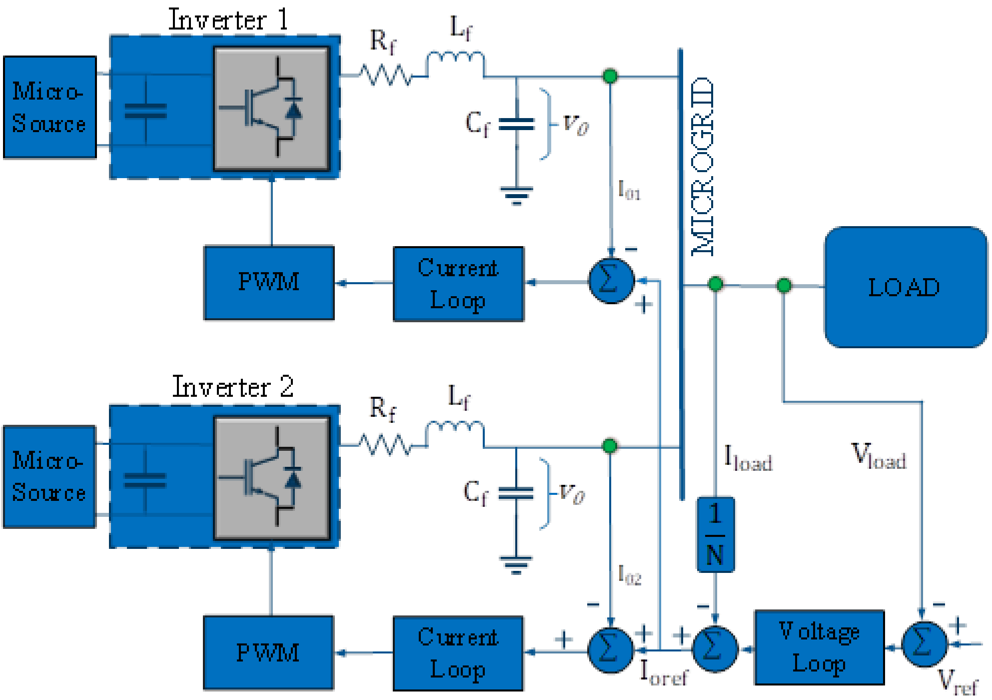

Figure 5 Block representation of concentrated control.

Droop-based methods are frequently used for interconnected synchronous generators and can be artificially crafted for parallel connected inverter-based DG units. Many studies (Chandorkar et al., 1993; De Brabandere et al., 2007; Gao & Iravani, 2008; Katiraei et al., 2004; Li et al., 2004; Nikkhajoei & Lasseter, 2009b; Piagi & Lasseter, 2006; Sao & Lehn, 2005) on controlling DG units via droop control are available. Droop-based methods are simple, reliable, do not require communication and are widely used, although they suffer from many drawbacks, such as inaccuracies in power sharing, frequency deviations and power quality issues. Communication-based methods are advantageous in terms of power sharing accuracy, good transient response and high power quality but require high costs because of the requirements of communication networks.

3.3. Classical conventional controllers

The following section discusses the classical communication-based and independent methods in detail.

3.3.1. Communication-dependent PSCs

These approaches require signal interconnection for data acquisition, voltage regulation and power sharing between various DG units in MGs, which can be implemented through technologies such as wireless communication, power line communication, or common-mode current communication. The advantages of using communication-based methods include superior performance in terms of voltage quality and balanced power sharing and elimination of the need for a secondary control architecture to gather the data from all DG units from the MG. However, they suffer from drawbacks such as limitations in the spatial flexibility of DG inverters, a reduction in system redundancy, and increased reliance on interaction signals, potentially lowering system reliability.

The communication-dependent methods can be classified into concentrated control (Shanxu et al., 1999; Prodanovic, 2000; Siri et al., 1992b; Vandoorn et al., 2013a; Wu et al., n.d.), master/slave control (Jiann-FuhChen & Ching-Lung Chu, n.d.; Petruzziello et al., n.d.-a; Siri et al., 1992a; Yunqing Pei et al., n.d.-a), and distributed control (Jingtao Tan et al., n.d.; Xiao Sun et al., 2003) and are briefly discussed in the following subsections.

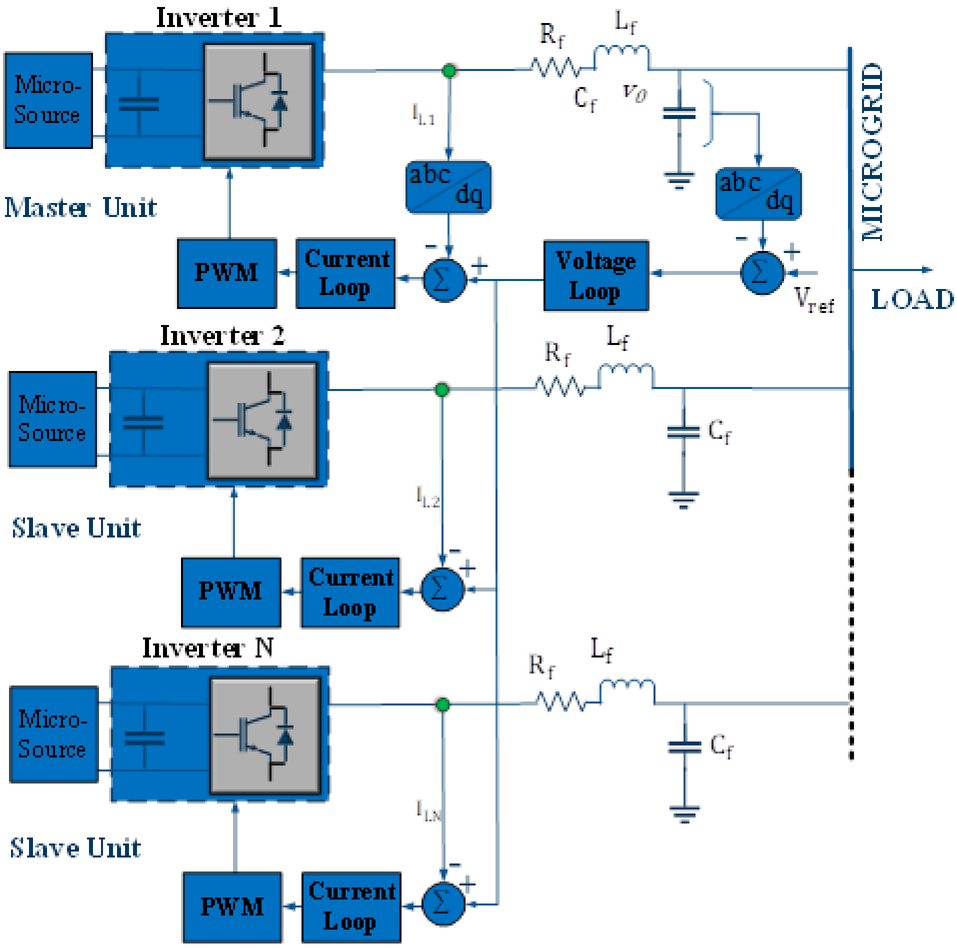

Figure 6 Block representation of master–slave control.

3.3.1.1. Concentrated control/centralized control

It operates independently of DG control loops and incorporates synchronization signals along with current control units, as shown in Figre 6. Each module is equipped with a PLL to ensure synchronization and maintain uniformity in the frequency and phase of the output voltage for each DG (Asadi, Eskandari, Mansouri, Chaharmahali, et al., 2022). The load-sharing modules evaluate the overall energy demand and determine the appropriate current that each module needs to supply. This calculated reference current is then distributed across all parallel-connected DG units through a high-bandwidth communication system (HBWCL), ensuring accurate current allocation and effective load distribution.

A communication-based centralized controller is used to improve the current sharing performance among DG units in the steady state as well as transient conditions in Ref. (Alsafran & Daniels, 2020; Espín-Sarzosa et al., 2020). A controller to provide improved frequency regulation ancillary services via a plug-in hybrid electrical vehicle and a communication-based controller is discussed in (Fakhari Moghaddam Arani & Mohamed, 2018). However, the management of harmonics and the circulation current in parallel DGs requires HBWCL, which reduces the reliability and scalability of this method.

3.3.1.2. Master slave control

This strategy is inspired by conventional power systems, where a slack bus maintains voltage and frequency, and all other buses supply the load. In MG, this concept is implemented by designating one inverter as the master, which maintains system synchronization, while the remaining inverters act as slaves, either injecting or absorbing active/reactive power on the basis of the master's instructions (Yunqing Pei et al., n.d.-b). As illustrated in Figure 7, the master inverter functions in voltage control mode, maintaining the output voltage by following a reference signal. Moreover, the slave inverters operate in current control mode, adjusting their output on the basis of the current provided by the master. This strategy eliminates the dependency on PLL signals and facilitates precise power sharing among the units.

However, despite its simplicity and ease of implementation, this control approach has several significant limitations. For example, failure of the master inverter can lead to the collapse of the entire MG, introducing a single point of failure. Additionally, this method struggles to handle output current transients effectively since only the master's output current is directly managed. To overcome these challenges, advancements such as dynamic role shifting, where the master role is periodically assigned to different inverters, have been introduced to enhance system reliability (Petruzziello et al., n.d.-b). Furthermore, active and reactive power-sharing communication methods have been employed to enable the inverter with the highest power output to assume the master role, supporting plug-and-play capability for DG units and optimizing overall performance. Multiple master/slave control systems have also been developed in (Mortezaei et al., 2018) to enhance voltage stability and frequency regulation, demonstrating improved performance under dynamic load conditions. Another enhancement in (Chaudhary et al., 2021) involves the use of an oscillating master strategy, where the master role alternates on the basis of the highest active power flow, thereby improving power-sharing accuracy and reliability, although it may occasionally result in synchronization errors.

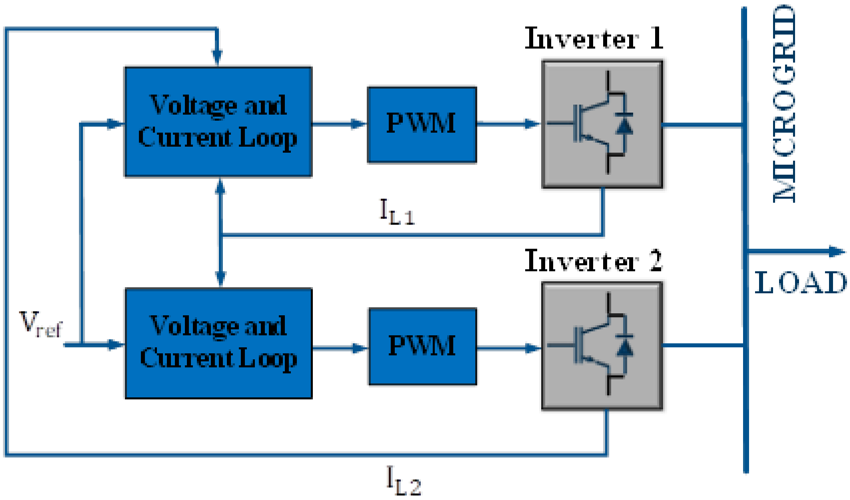

Figure 7 Classification of PSC methods at the primary level of the hierarchy.

3.3.1.3. Distributed control

Distributed control eliminates the need for a central controller by allowing each inverter connected in parallel to operate independently (Vandoorn et al., 2013b). This method is characterized by instantaneous and average current sharing, ensuring effective load distribution and voltage regulation among parallel inverters. A communication network between DG units is needed to synchronize the voltage and current at the PCC.

Key techniques within distributed control include current limiting control, which minimizes harmonics and limits the inverter output current to maintain power quality (Ogasawara et al., 1992); average and instantaneous current sharing, which ensures synchronized references for voltage and current, improves load distribution and enhances regulation (Vasquez et al., 2010); one-cycle control, which reduces circulating currents between inverters by combining vector and bipolar operations with a simplified communication framework (Chen & Smedley, 2008); circular chain control (3C), which connects inverters in a circular configuration using internal current control to achieve equal current sharing (Sun et al., 2006); and weighted current distribution, which ensures proportional current sharing among inverters with varying power ratings by using a simple additional circuit for dynamic response and stability (Wu et al., 2007). Figure 8 shows the block diagram of circular chain control.

Distributed control offers several advantages, including improved power quality, scalability, and resilience to single-unit failures. If one inverter fails, it can be disconnected without disrupting the parallel operation of other units. The system supports modular expansion, allowing new inverters to be seamlessly integrated, and ensures accurate power sharing and voltage regulation among DG units.

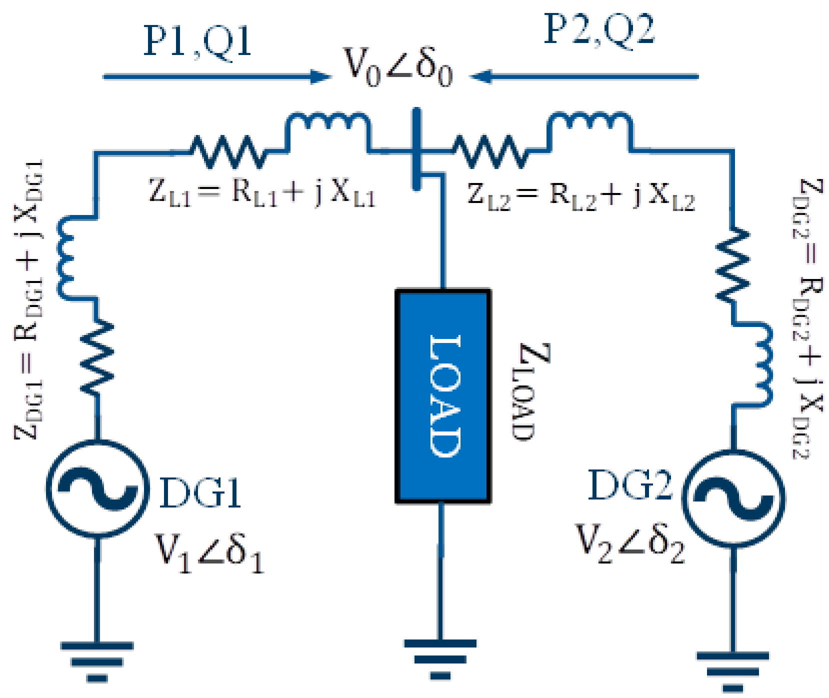

Figure 8 Typical droop characteristics of conventional droop control. *Source:* Olivares et al., (2014).

Despite these benefits, distributed control also has limitations. The reliance on interunit communication introduces vulnerabilities, such as the risk of communication failure, delays, or increased costs associated with establishing and maintaining the communication infrastructure (Asadi, Eskandari, Mansouri, Chaharmahali, et al., 2022). Additionally, the system's flexibility is constrained by the need for synchronization between units, and its scalability is limited as the communication complexity increases with the number of inverters (Asadi, Eskandari, Mansouri, Chaharmahali, et al., 2022).

To overcome these challenges, several improvements have been proposed. Sparse communication networks have been introduced to reduce the reliance on expensive communication links while maintaining accurate load sharing and voltage regulation. Two-layer control structures decouple voltage and frequency in the first layer and active and reactive power in the second layer, ensuring improved stability and power-sharing accuracy (Xin et al., 2015). Advanced current control techniques, such as partial feedback linearization, enhance active and reactive power-sharing capabilities by accounting for known system parameters (Shafiee et al., 2014). Additionally, distributed primary control via modern control algorithms has been shown to improve the dynamic response and reduce synchronization errors (Toro & Mojica-Nava, 2016). Overall, these advancements aim to address the limitations of distributed control and improve system reliability, flexibility, and performance while reducing costs and complexity.

3.3.2. Summary of Communication-dependent PSCs

This section highlights the advantages, disadvantages and key improvements in communication-dependent methods in tabular form.

3.3.3. Communication-independent PSCs

The communication-free control strategies are primarily based on the traditional droop control approach. These controls are essential for managing the power output of DGs while also regulating MG parameters such as voltage and frequency to ensure system stability. Figure 1 provides an overview of the various droop-based control techniques, which are explored in detail in the subsequent sections, starting with classical control methods.

3.3.3.1. Traditional droop control (TDC)

The basic operating principle of droop-based methods is to balance the input and output powers of synchronous generators in the power grid. In this context, the synchronous generator receives mechanical power (Pm) as input and delivers electrical power (Pe) as output. When Pm>Pe, the generator rotor speeds up, leading to an increase in frequency, and vice versa. Similarly, variations in the reactive power output result in changes in the magnitude of the voltage.

The droop-based power-sharing mechanism is adapted for parallel-connected, converter-based DG units. It emulates the behavior of conventional synchronous generators by modifying real power in response to frequency changes (P-f) and reactive power based on voltage (Q-V). This enables proportional power sharing among DG units without relying on communication networks, making it ideal for MG applications. The analysis of TDC is based on the equivalent circuit of parallel connected inverters shown in Figure 9. where Z_{L1} and Z_{L2} are the impedances of the lines connecting DG1 and DG2 to the PCC. The output impedances of DGs are represented by Z_{DG1} and Z_{DG2}. The output voltages of the DG1, DG2 and PCC voltages are V_1, V_2 and V_0, and the phase angles are δ_1, δ_2 and δ_0 , respectively.

Table 1 Summary of communication-independent power sharing control.

Control Method	Concept	Merits	Demerits	Key Improvements/Notes
Centralized Control	Uses PLL for synchronization	- Enhances current sharing in steady and transient conditions. - Provides uniform frequency and phase synchronization.	- High reliance on HBWCL reduces reliability. - Limited scalability. - Vulnerable to harmonics and circulating currents.	- Used for frequency regulation services. - Requires advanced harmonic and communication management techniques.
Master-Slave Control	Designates one inverter as the master and others as slave to maintain synchronization.	- Simple implementation. - Eliminates PLL requirements. - Ensures precise power sharing.	- Single point of failure if the master inverter fails. - Struggles with transient output currents.	- Dynamic role-shifting to periodically reassign the master role. - multimaster/slave and oscillating master strategies improve reliability and accuracy.
Distributed Control	Eliminates the central controller by allowing parallel inverters to operate independently while synchronizing via communication networks	- Improved power quality. - Scalable and modular. - Resilient to single-unit failures. - Accurate load sharing and voltage regulation.	- Communication dependent, vulnerable to failures or delays. - Increased costs for communication infrastructure. - Synchronization requirements limit flexibility.	- Sparse communication networks reduce dependency on costly links. - Two-layer control improves voltage/frequency decoupling and power-sharing accuracy. - Modern algorithms enhance dynamic response and reduce synchronization errors.

The real and imaginary power outputs of the ith DG unit when connected across two nodes by a line impedance are given as (Cheng et al., 2009; Dai et al., 2004; Guerrero et al., 2008; Mishra, 2009; Tuladhar et al., 1997).

$$P_i = \frac{1}{Z_i}[(V_i V_0 \cos\delta_i - V_0^2)\cos\theta_i + V_i V_0 \sin\delta_i \sin\theta_i] \quad (1)$$

$$Q_i = \frac{1}{Z_i}[(V_i V_0 \cos\delta_i - V_0^2)\sin\theta_i + V_i V_0 \sin\delta_i \cos\theta_i] \quad (2)$$

Where: δ and θ are the phase and impedance angles, respectively. The voltage at the PCC, inverter output voltage and impedance magnitude are denoted by V_0, V_i and Z_i, respectively. In inductive lines, the real part of Z can be neglected. In practical systems, the phase difference 〖δ〗_i between bus voltages is small, leading to cos⁡〖δ_i 〗=1 and sin⁡〖δ_i 〗=δ_i.

Hence, the power transfer equations in (1) and (2) can be simplified to (3) and (4).

$$P_i = \frac{V_i V_0}{X_i}\delta_i \quad (3)$$

$$Q_i = \frac{V_0}{X_i}(V_i - V_0) \quad (4)$$

As indicated by equations (5) and (6), the generation of reactive power is directly tied to the difference in voltage magnitude, and the real power output from the DG unit is entirely based on the phase angle difference.

Figure 9 illustrates this behavior, where the relationship between the real power output (Pi) of the ith inverter and the frequency (f) can be mathematically expressed as:

$$f_i - f^* = -SP_{Pi}(P_i - P_i^*) \quad (5)$$

$$SP_{Pi} = \frac{\Delta f}{P_{imax}} = \frac{f_{max} - f_{min}}{P_{imax}} \quad (6)$$

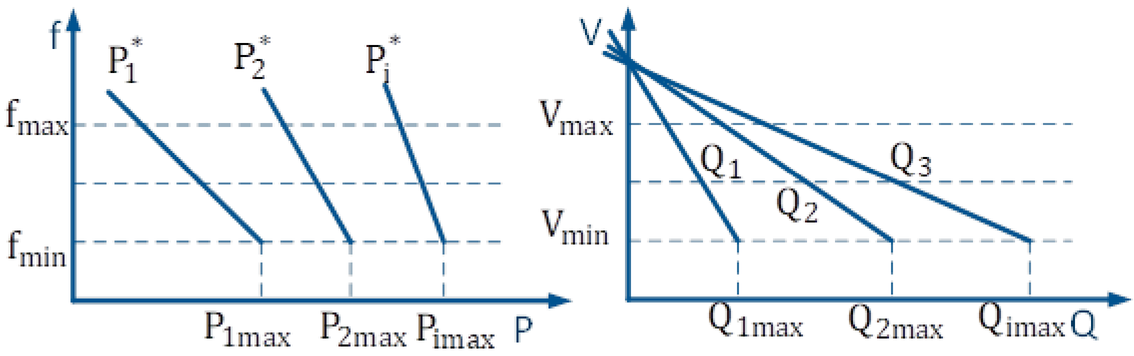

Figure 9 Typical droop characteristics of traditional droop control. *Source:* Olivares et al., (2014).

In this equation, Pi represents the actual real power output of the ith inverter, Pimax denotes the maximum real power capacity of the ith DG inverter, ωmin signifies the minimum permissible operating frequency, and SPpi is the slope of the P–f droop characteristic curve and is termed the droop coefficient.

Initially, during grid-connected operation, each inverter-based DG unit is engineered to deliver a predetermined real power output (Pi) at the standardized base frequency (ω). This base frequency is maintained by the robust utility grid.

Upon transitioning to islanded mode, the power outputs of each inverter must swiftly adapt, adhering to their specific droop characteristics. This adaptation is crucial to ensure that the collective power generated by the DG units aligns with the demand of critical loads within the MG. This dynamic response allows the MG to establish a new equilibrium at a modified steady-state frequency (ω).

Following a similar principle, the magnitude setpoint of each DG's output voltage can be adjusted on the basis of a designated Q–V droop scheme to manage the reactive power flow within the MG. This relationship can be mathematically represented as follows:

$$V_i - V^* = -\mathrm{SP}_{Qi}(Q_i - Q_i^*) \quad (7)$$

$$SP_{Qi} = \frac{\Delta V}{Q_{imax}} = \frac{V_{max} - V_{min}}{Q_{imax}} \quad (8)$$

The reactive power output (Qi) of the i^{th} DG is governed by a Q-V droop mechanism, where it is adjusted in relation to the voltage magnitude (|V|) compared with a minimum threshold (|Vmin|). In this relationship, Q_{imax} represents the maximum reactive power capacity of the i^{th} DG, and SP_{Qi} (negative) is the slope of the droop characteristic curve. When the MG is connected to the main grid, the dispatched reactive power of the i^{th} DG unit is denoted as Q*i,* and the corresponding voltage magnitude at the point of common coupling (PCC) is V.

Figure 9 illustrates the ideal scenario of reactive power sharing among DG units via voltage droop control, and Figure 10 depicts the graphical block representation of the TDC method.

The power components (P & Q) of the DGs are determined by the output currents (I_0) and voltages (V_0) from the inverter units. By applying droop coefficients (SP_{P1}, SP_{Q1}) to the power components and comparing these with the reference frequency (f^*) and voltage (V^*), operational frequency (f) and voltage (V) signals are generated.

The droop coefficients, SP_{Pi} & SP_{Qi}, are inversely proportional to the DG inverter power rating. This ensures that the load power demand is shared proportionally to their respective capacities. Equations (9) and (10) illustrate this relation.

$$SP_{P1}{\cdot}P_1 = SP_{P2}{\cdot}P_2 = \cdots = SP_{Pi}{\cdot}P_i \quad (9)$$

$$SP_{Q1}{\cdot}Q_1 = SP_{Q2}{\cdot}Q_2 = \cdots = SP_{Qi}{\cdot}Q_i \quad (10)$$

TDC is simple to implement, reliable and does not require communication, but it has the following drawbacks:

1. In a power grid with inductive line impedances, traditional control of real and reactive power, which assumes negligible line resistance, functions effectively. However, this approach raises concerns when it is applied to an LVMG, where the feeder impedance is not primarily inductive and where the line resistance cannot be ignored. In this scenario, changes in the phase angle or voltage magnitude affect both real and reactive power flows and result in significant coupling between real and reactive power flows, particularly during transients (Li & Kao, 2009; Sao & Lehn, 2005; Yu et al., 2010).

2. In an AC MG, the system maintains a consistent voltage frequency across the AC bus, ensuring accurate active power sharing under P–ω control. However, a complication of Q–V droop control is that the terminal voltages of DG units can differ because of voltage drops caused by mismatched line impedances. Consequently, the Q–V droop scheme results in a reactive power imbalance (He & Li, 2012; Li & Kao, 2009; Vasquez et al., 2009).

3. TDC is designed primarily for power sharing of fundamental components of powers and fails to address the sharing of harmonic power in the presence of nonlinear loads (Tuladhar et al., 1997, 2000).

4. In contrast to the substantial inertia provided by synchronous generators in larger power systems, MGs, particularly those with high penetration of power electronics interfaced with DGs, exhibit low inertia. This characteristic leads to significant frequency variations during isolated operation in TDC control (He & Li, 2012; Katiraei & Iravani, 2006).

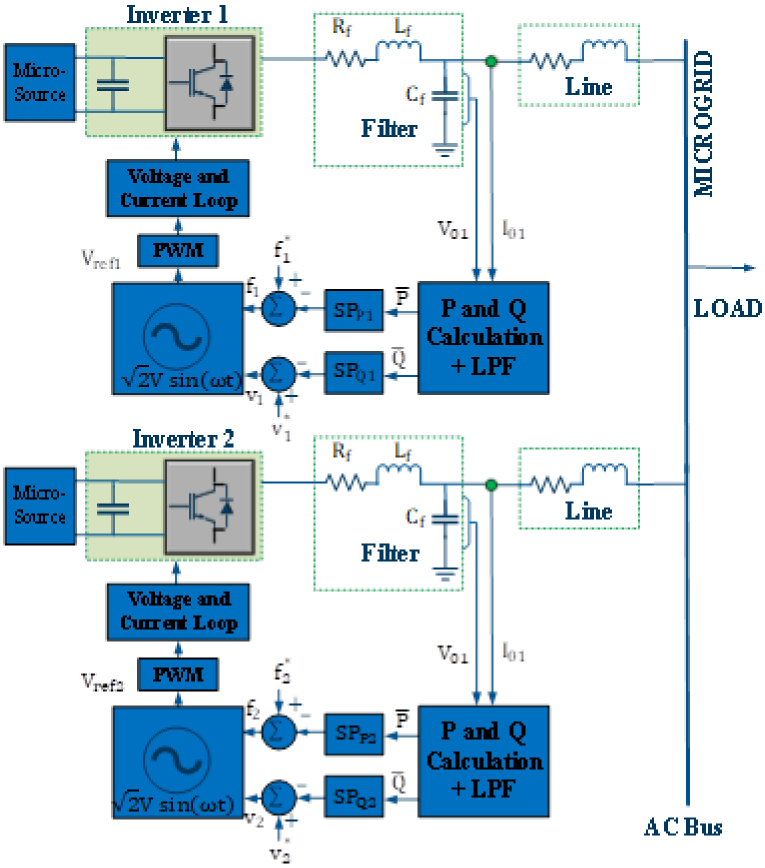

Figure 10 Block diagram of the traditional droop control strategy.

3.3.3.2. Reverse droop control method

When employed in a power grid with predominantly inductive line impedances, the traditional droop method for real and reactive power control neglects the line resistance, which may be sufficient under those circumstances. However, this approach becomes problematic in LV MGs, where feeder impedances are not predominantly inductive, and the resistance component (R) cannot be ignored. This issue is particularly significant for DG units interfaced with power electronics, which lack a grid-side inductor or transformer, resulting in minimal output inductance. Under these conditions, even minor changes in the phase angle or voltage magnitude can significantly affect both the real and reactive power flows [7,24,59].

To address this issue effectively, the reverse droop control strategy was proposed in reference (Li & Kao, 2009; Sao & Lehn, 2005; Yu et al., 2010). In this control, an increase in real power is associated with the voltage variation $(V_i - V_0)$, and an increase in reactive power is associated with a change in the power angle (δ) (Dan Wu et al., 2014).

$$P_i = \frac{V_0}{Z_i}(V_i - V_0) \quad (7)$$

$$Q_i = \frac{V_i V_0}{Z_i}\delta_i \quad (8)$$

Frequency regulation is achieved by managing the power angle through the control of reactive power consumption. Similarly, controlling the active power regulates the voltage as given in the control equations (Guerrero et al., 2005, 2007; Sao & Lehn, 2008; Yu et al., 2010):

$$f_i - f^* = SP_{Pi}(Q_i - Q_i^*) \quad (9)$$

$$V_i - V^* = -SP_{Qi}(P_i - P_i^*) \quad (10)$$

This approach enhances control effectiveness in LV AC MGs characterized by predominantly resistive transmission lines (Guerrero et al., 2007). However, the performance of this method is heavily dependent upon accurate knowledge of system parameters, which can considerably limit its practical deployment. Another limitation of this method is its low responsiveness to variations in the grid voltage, which depends on the magnitude of the voltage itself. This leads to deteriorated dynamic performance. Furthermore, since the voltage is measured locally, achieving an accurate distribution of real power in resistive grids becomes more complex.

3.3.4. Modified droop control methods

To overcome the drawbacks of the classical methods discussed in the above sections, modified droop control methods have been suggested in the literature and are discussed in the following section.

3.3.4.1. Virtual frame transformation methods

A modification is suggested for the TDC to overcome the drawbacks of low X/R ratio lines (Olivares, Mehrizi-Sani, Etemadi, Cañizares, et al., 2014) in the form of the Virtual Frame Transformation (VFT) method in the form of either P-Q or $\omega - V$ (Vasquez et al., 2009).

Virtual P-Q frame transformation (De Brabandere et al., 2007; Lee et al., 2009) is based on converting active and reactive powers from the time domain into a virtual frame of reference. It is achieved via the orthogonal linear rotational transformation method. This allows the decoupling of the active and reactive power, simplifying the control strategy.

Under the assumption of mixed line impedance characteristics and a small phase angle δ_i, equations (1) and (2) are transformed via orthogonal virtual frame transformation as follows:

$$\begin{bmatrix} P' \\ Q' \end{bmatrix} = T \begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} \sin\theta & -\cos\theta \\ \cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} P \\ Q \end{bmatrix} \tag{11}$$

$$P' = \frac{X}{Z} P - \frac{R}{Z} Q \tag{12}$$

$$Q' = \frac{R}{Z} P + \frac{X}{Z} Q \tag{13}$$

Even though the line impedance includes a combination of resistive and inductive elements, P/Q decoupling is accomplished as though the network was entirely inductive. The transformed variables P' and Q' of the active and reactive powers are decoupled from each other. Generally, a precise R/X ratio may not be available; however, an estimated R/X ratio can often be adequate to apply the method (Han et al., 2016; J. C. Vasquez et al., 2009).

Like the P-Q frame transformation, the virtual frequency/voltage frame ω'-V' can be expressed as (Li & Li, 2009a, 2009b, 2011):

$$\begin{bmatrix} \omega' \\ V' \end{bmatrix} = \begin{bmatrix} \sin\theta & \cos\theta \\ -\cos\theta & \sin\theta \end{bmatrix} \begin{bmatrix} \omega \\ V \end{bmatrix} = T_{PQ} \begin{bmatrix} \omega \\ V \end{bmatrix} \tag{14}$$

$$\omega' = \frac{X}{Z} \omega - \frac{R}{Z} V \tag{15}$$

$$V' = \frac{R}{Z} \omega + \frac{X}{Z} V$$

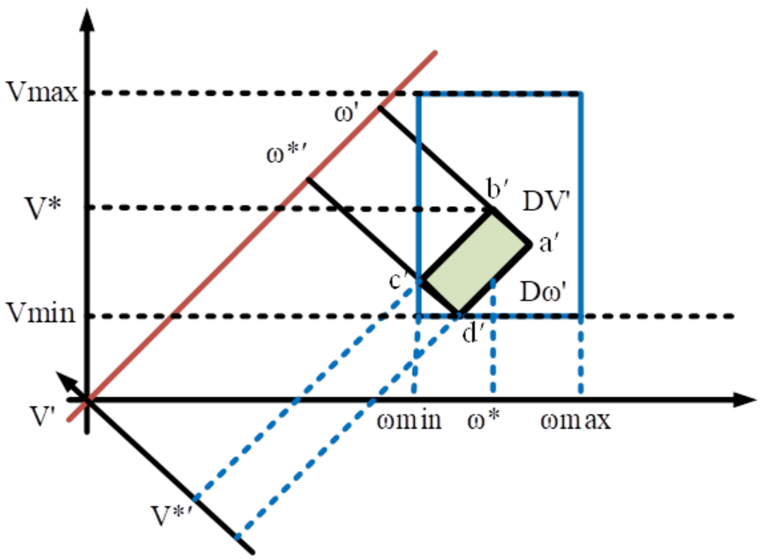

Figure 11 **ω**'-V' VFT.

3.3.4.2. $(P - Q) \cdot f / (P + Q) \cdot V$ *method*

In transmission lines that have both resistive and inductive characteristics, changes in active power can influence reactive power and vice versa. This interdependence makes it difficult to control each type of power separately. However, by taking into account the effects of complex impedance, it is possible to decouple active and reactive power.Considering the impact of complex impedance, active and reactive power decoupling can be achieved via the method suggested in (De Brabandere et al., 2007; Li et al., 2004). The control equations are given as

$$f_i - f^* = -D_{Pi}\{(P_i - Q_i) - (P_i^* - Q_i^*)\} \quad (16)$$

$$V_i - V^* = -D_{Qi}\{(P_i + Q_i) - (P_i^* + Q_i^*)\} \quad (17)$$

Compared with the conventional droop method, this method offers efficient dynamic performance even in the case of MV MGs where the transmission line X/R ratio is nearly one (Han et al., 2016).

3.3.4.3. $P - f \,/\, Q - \dot{V}$ *method*

Mismatched line impedance conditions cause inaccurate reactive power sharing among parallel DG units in TDC. The $P - f \,/\, Q - \dot{V}$ method proposed in (Lee et al., 2010, 2013) is designed to make the sharing of reactive power among DG units in an MG independent of the line impedance. A notable characteristic of this method is that its effectiveness depends on the initial conditions of the system, which is a point of consideration when the control strategy is implemented. The control equations are given by:

$$f_i = f_i^* - D_{pi}(P_i - P_i^*) \quad (18)$$

$$\dot{V}_i = \dot{V}_i^* - D_{Qi}(Q_i - Q_i^*) \quad (19)$$

Where: $\dot{V}_i^*$ is the nominal value of $\dot{V}_i$, which is set to 0 V/s. After any transient change, $\dot{V}_i$ is set to zero to ensure stable operation. Owing to the differences in the restoration processes among various DGs (Han et al., 2016), each DG might have a different setpoint for voltage or reactive power. Hence, the power sharing accuracy is not completely improved with this method. The block diagram in Figure 12 represents the control structure of this method.

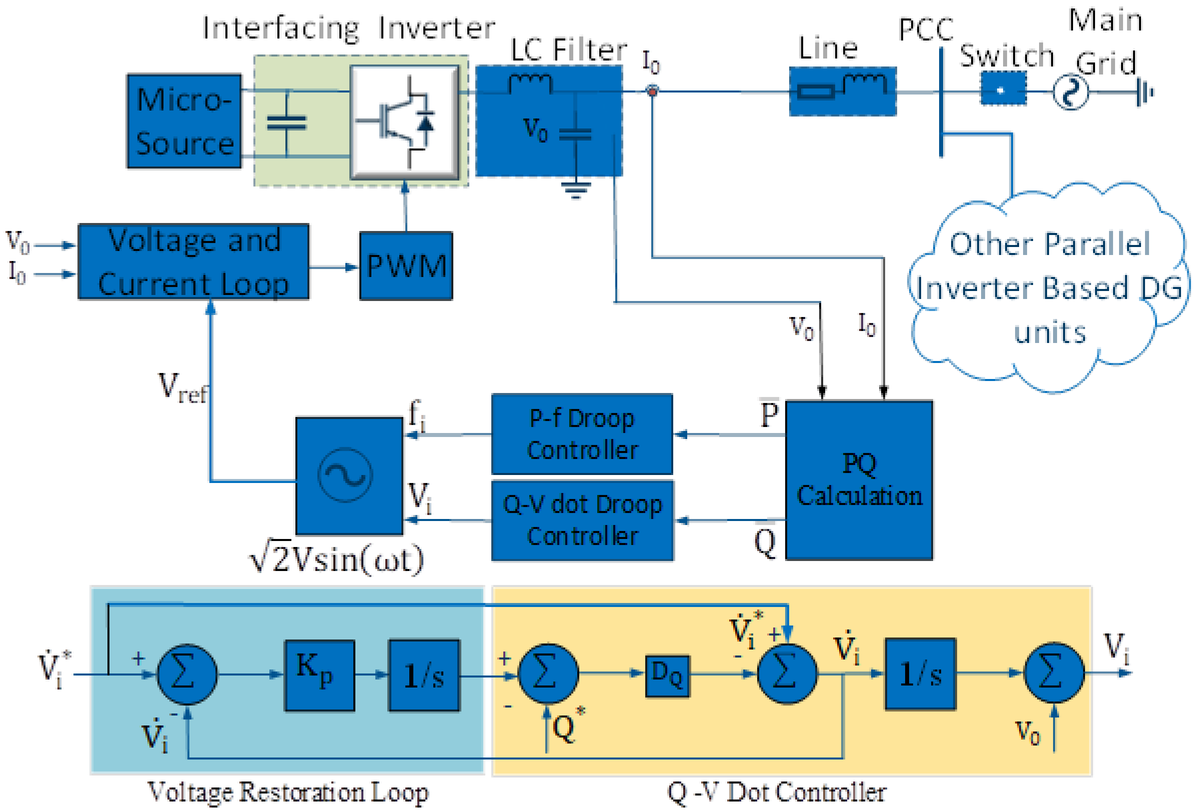

Figure 7 Block diagram of the P-f/Q-V Dot method.

$$V_i = \dot{V}_i^* + \int \dot{V}_i \, d\tau \quad (20)$$

A modified voltage restoration loop was proposed in (Zhou & Cheng, 2019) to address the problem of setpoint deviation. The performance of the Q – V˙ method is degraded when the equivalent impedance is complex. Compared with purely inductive cases, little attention has been given to purely resistive cases (Guerrero et al., 2007; Vandoorn et al., 2012). In (Guerrero et al., 2007), the output impedance of parallel DGs is shaped to be resistive, where the Q – V˙ droop equation is replaced by the P – V˙ droop control equation. With the resistive output impedance, the overall system is more damped, and the harmonic current is automatically shared (Vandoorn et al., 2012). However, if the mismatch of the feeder impedance is ignored, it will have great limitations in real applications. A virtual complex impedance-based P – V˙ droop method that combines the advantages of both the virtual impedance-based method (Tuladhar et al., 2000) and the Q – V˙ droop method (Lee et al., 2010) was proposed in (Chen et al., 2021) to solve the power-sharing problem of the LVMG.

3.3.4.4. Virtual impedance droop control (VIDC)

Traditional droop control methods, while widely used, often face challenges such as inaccurate power sharing due to mismatched line impedances and voltage drops across distribution lines (De Brabandere et al., 2007; Fu et al., 2012; He & Li, 2012; Li et al., 2004; Nikkhajoei & Lasseter, 2009b; Sao & Lehn, 2005). To overcome these limitations, VIDC introduces a virtual impedance layer that modifies the electrical behavior of DG units without altering the physical hardware (Engler, 2000; Chiang et al., 2001; De Brabandere et al., 2007; Guerrero et al., 2005, 2006, 2009, 2013; Guerrero, Vasquez, Matas, de Vicuna, et al., 2011; Micallef et al., 2014; Yao et al., 2000). This approach ensures proportional power sharing and enhances MG performance under diverse operating conditions.

Virtual impedance is implemented by adding a virtual resistive, inductive, or capacitive component to the control loop of the inverter (Engler, 2000; Chiang et al., 2001). This modification allows the inverter to emulate specific electrical characteristics that influence the power flow between DG units and the MG.

A block diagram of the virtual impedance method is shown in Figure 13. The reference voltage V_{ref} with fast virtual impedance droop control is obtained by subtracting the voltage drop with virtual impedance $Z_V I_0$ from the reference output voltage obtained from the droop controller V^* as follows:

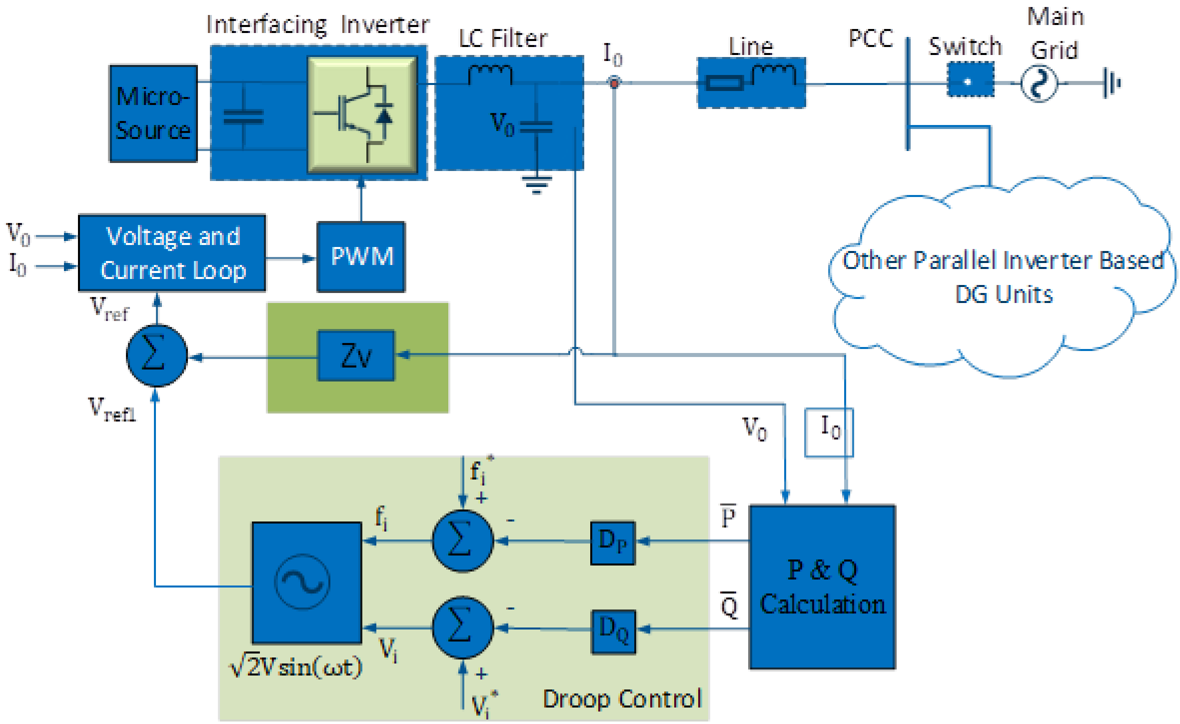

Figure 8 Block diagram of VIDC.

$$V_{ref} = V^* - Z_V I_0 \quad (21)$$

In real-time implementations, virtual inductive output impedance is realized by first calculating the time derivative of the sensed fundamental output current and then the output voltage reference characteristics are drooped in proportion to that current.

The equivalent circuit and phasor diagram of the virtual impedance method are shown in Figure 14 (a) and (b), respectively. The voltage drops due to the virtual impedance and line impedance are $R_v\bar{I}$ and $jX_v\bar{I}$ and $R_l\bar{I}$ and $jX_l\bar{I}$, respectively. The DG output voltage is E, and the voltage at the PCC is V_{PCC}, resulting in angles of α and φ. $\bar{I}$ is the inverter output current.

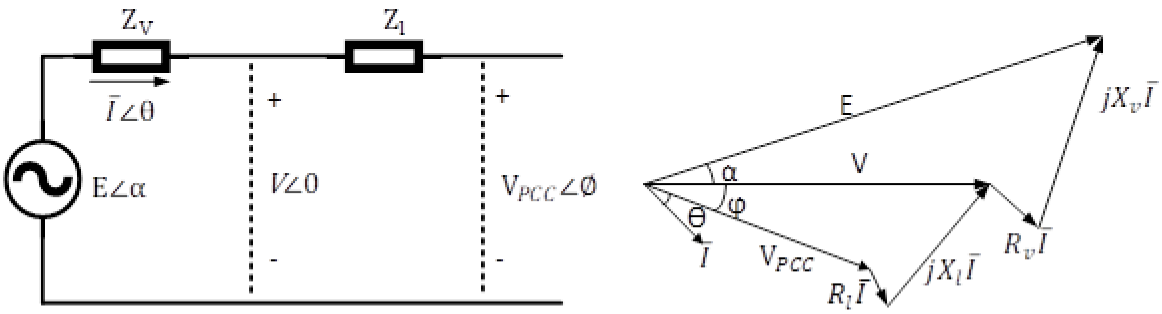

Figure 9 Virtual impedance method (a) Equivalent circuit (b) Block diagram.

Usually, the virtual output impedance values are greater than the line impedance (Micallef et al., 2014).

The calculation of the virtual impedance is based on the voltage drops across inverters. The voltage drops across the total impedance, which is the sum of the line impedance and inverter impedance of the MG inverters, and is assumed to be equal for balanced reactive power sharing. This is called the summation approach (Rowe et al., 2013).

$$V_{drop1} = (Z_{l1} + Z_{V1})I_{l1} = V_{drop2} = (Z_{l2} + Z_{V2})I_{l2} \tag{22}$$

Where: Z_{V1} & Z_{V2} are the virtual output impedances and where Z_{l1} and Z_{l2} are the line impedances of inverters 1 and 2, respectively.

To determine the virtual impedance of inverter 1, which emulates the line impedance, the virtual impedance of inverter 2 is assumed to be zero. Z_{V2} can be fixed to zero if $Z_{l2} > Z_{l1}$. Then, Z_{V1} can be calculated as

$$Z_{V1} = Z_{l1} - Z_{l2} \tag{23}$$

The above-discussed summation method may reduce the virtual output impedance but improve the reactive power sharing among inverters. For either mainly inductive or restive distribution lines, by adjusting the virtual impedance properly, the active and reactive powers can be decoupled.

Modifications have been reported in the virtual output impedance strategy in the literature for voltage unbalance compensation (Savaghebi et al., 2013) to improve reactive power compensation and dynamic performance via active and reactive power coupling compensation (Peng et al., 2019) to achieve better reactive power and harmonic sharing (Bouzid et al., 2015).

3.3.4.5. Virtual flux droop (VFD) control

Compared with conventional voltage droop methods, VFDs can achieve accurate power sharing with much lower frequency deviations under steady-state conditions and better voltage regulation under transient conditions (Hu et al., 2014), leading to improved power quality and system stability.

The VFD adjusts the virtual flux rather than the inverter output voltage to achieve autonomous power sharing.

The virtual flux at the inverter terminal and common bus is given as (Hu et al., 2014).

$$|\psi_{Vi}| = \frac{|V_i|}{\omega}, \qquad \phi_{fVi} = \phi_{Vi} - \frac{\pi}{2} \tag{24}$$

$$|\psi_E| = \frac{|E|}{\omega}, \qquad \phi_{fE} = \phi_E - \frac{\pi}{2} \tag{25}$$

Where: $|\psi_{Vi}|$ and ϕ_{Vi} are the magnitude and phase angle of the virtual fluxes associated with V_i and where $|\psi_E|$ and and ϕ_E are the magnitude and phase angle of the virtual fluxes associated with E, respectively.

The active and reactive power drawn from the ith inverter is given as –

$$P_i = \frac{\omega}{L_i}\psi_E\psi_{V_i}\delta_i \tag{26}$$

$$Q_i = \frac{\omega}{L_i}|\psi_E|(|\psi_{Vi}| - |\psi_E|) \tag{27}$$

The phase angle difference is $\delta_i = \phi_{Vi} - \phi_E = \phi_{fVi} - \phi_{fE}$. The active power can be regulated by controlling the flux phase angle difference δ_i. The flux magnitude difference $(|\psi_{Vi}| - |\psi_E|)$ can be varied to control the reactive power sharing. The VFD droop equations are given as (Hu et al., 2014).

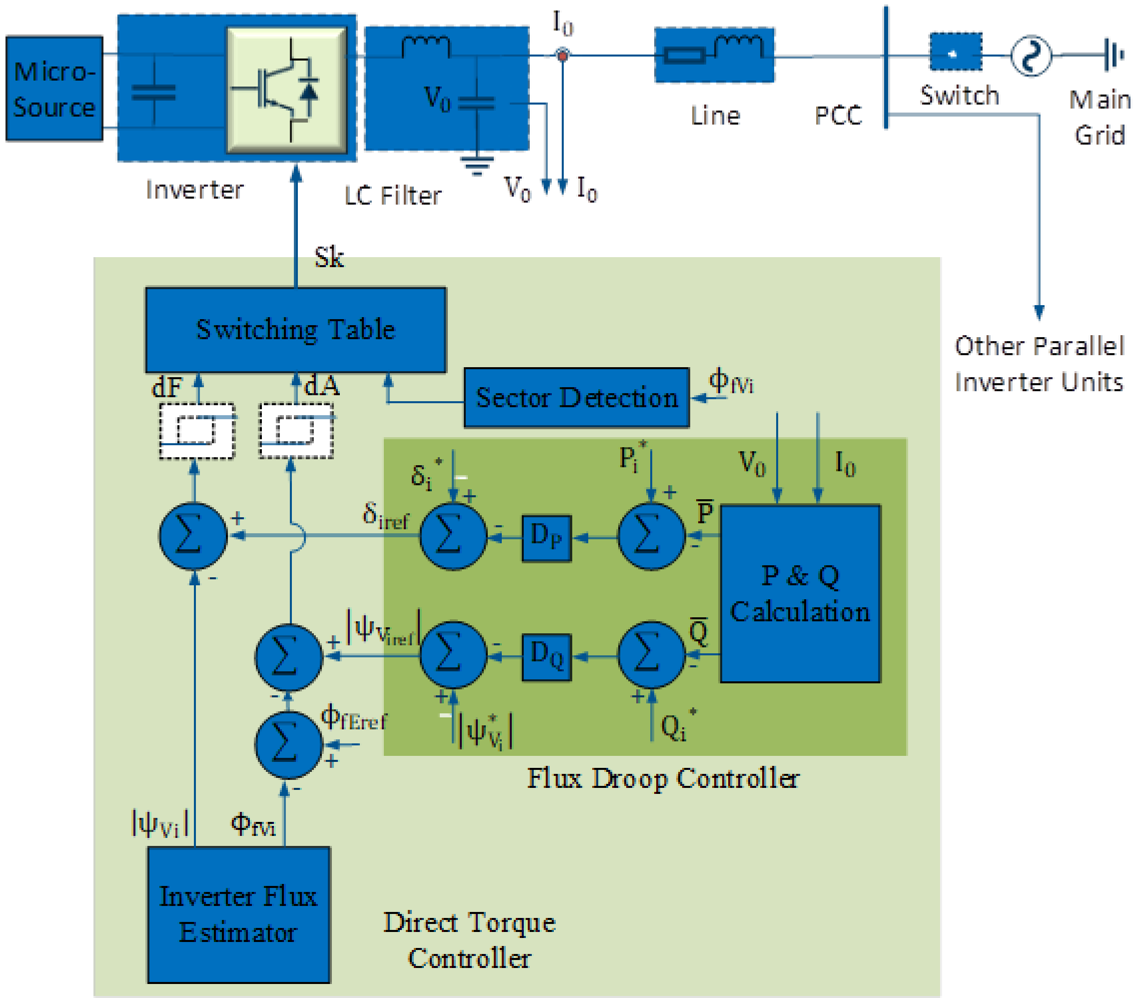

Figure 10 Block diagram of the virtual flux droop method.

$$\delta_i = \delta_i^* - D_{Pi}(P_i - P_i^*) \tag{28}$$

$$|\psi_{V_i}| = |\psi_{V_i}^*| - D_{Qi}(Q_i - Q_i^*) \tag{29}$$

Where: δ_i^* is the nominal phase angle difference and where $|\psi_{V_i}^*|$ is the nominal amplitude of the inverter flux. P_i^* and Q_i^* are the power ratings of the DG unit, and m and n are the droop coefficients. The block diagram of the VFD method is depicted in Figure 15. The VFD method simplifies the control structure by eliminating the need for multiple feedback loops and pulse-width modulation (PWM) modulators, which are required in the TDC method. By employing a DFC algorithm, this strategy regulates the virtual flux according to the droop controller, avoiding the use of proportional-integral (PI) controllers.

3.3.4.6. Angle droop controller

Angle droop control is a decentralized control strategy that is independent of communication requirements and is discussed in (Majumder et al., 2010; Majumder et al., 2009). This controller is useful for sharing real power among MG inverters with highly inductive network impedances (Kolluri et al., 2017).

Angle droop control assumes that all the voltage sources have constant amplitudes and operate exactly at a common frequency, e.g., 50 Hz. Measurements of angles are taken against a standard angular frequency commonly set at either 50 or 60 Hz (Majumder, Ledwich, et al., 2010). The network impedances are primarily inductive with a high X/R ratio (Majumder, Chaudhuri, et al., 2010). The power flow in such a system is given by

$$P_i = \frac{V_i V_0}{X_{i0}} \sin(\delta_i - \delta_0) \tag{30}$$

Assuming that the phase angle difference is small

$$\sin(\delta_i - \delta_0) = (\delta_i - \delta_0) \tag{31}$$

$$P_i \frac{X_i}{V_i V_0} = (\delta_i - \delta_0) \tag{32}$$

$$(\delta_i - \delta_0) \cong k_{ij} P_i \tag{33}$$

Where: $k_{ij} = \frac{X_{ij}}{V_i V_j}$ assumes a constant value that is based on the voltages at these points and the impedance of the line connecting them.

The given equation clearly shows that the flow of active power between two points in the network can be managed by adjusting the phase angles of the voltages produced by the inverters. This principle underpins the operation of the angle droop controller (Majumder et al., 2009):

$$\delta_i = \delta_i^* = -D_{Pi} (P_i - P_i^*) \tag{34}$$

$$V_i - V_i^* = -D_{Qi}(Q_i - Q_i^*) \tag{35}$$

Where: D_{Pi} and D_{Qi} are droop coefficients and where $(.)^*$ represents nominal rated values.

Angle droop controller-based MG inverter systems provide better stability margins [76], [79] and regulate their frequency at its setpoint [75] without steady-state error. One of the drawbacks of this method is that if the local inverter controllers are not synchronized, the small inaccuracies in their timing crystals can cause the inverters' frequencies to drift apart. Over time, this can push the phase alignment beyond acceptable boundaries, resulting in potential instability in the system [47]. To counter this, some experts recommend using a controller area network bus or leveraging the global positioning system for better synchronization among DG units [78].

3.3.4.7. $P - Q - V$ droop control

This method (Li & Li, 2011; Moawwad et al., 2013) aims to simultaneously improve voltage regulation and control active and reactive power at the PCC. The voltage adjustment follows the equation:

$$V = V^* + (D_P \cdot P) + (D_Q \cdot Q)$$

In this equation, V^* represents the reference voltage value set at the PCC. The variables D_P and D_Q are the droop coefficients for active and reactive power, respectively, and are dynamically adjusted in real time on the basis of the actual voltage level at the PCC. "This adjustment is facilitated through a lookup table, which likely contains predefined sets of coefficients corresponding to different voltage levels to ensure that the voltage remains within the desired range." The adjustment process uses a lookup table containing predefined coefficients for various voltage levels to maintain the voltage within an acceptable range.

3.3.4.8. Arctan droop

Traditional droop control has a linear relationship with power and frequency. The arctangent-based method (Rowe et al., 2013) introduces a nonlinear relationship by incorporating an arctan function into the active power droop equation. This nonlinear approach allows the slope of the droop to vary with active power, providing a flexible response to changes in power.

The advantage of this method is that it is able to maintain the frequency within a specified range despite fluctuations in power. The control function is given as

$$f_i = f^* - \frac{a_P}{\pi}\left(\arctan\left(\rho(P_i' - P^{*\prime})\right)\right) \tag{36}$$

$$V_i = V^* - D_Q(Q_i - Q_i^*) \tag{37}$$

$$P' = \frac{X}{Z} P - \frac{R}{Z} Q \tag{38}$$

Where: a_P is the arctan bounding multiplier and where ρ is the arctan droop coefficient.

The arctan function inherently provides a softer response as the input moves away from zero, which means that for large deviations in power, the change in frequency is less abrupt than that of linear droop control.

3.3.4.9. Modified droop with a lowpass filter

A novel method to damp low-frequency oscillations via virtual inertia and an adaptive frequency restoration loop was proposed in (Eskandari et al., 2019). Virtual inertia and virtual damping are created by adding a time delay into the control system via a low-pass filter of the power converters, which mimics the effect of physical inertia. A block diagram of the droop controller with a modified low-pass filter is shown in Figure 16. To supply the control loop with average power values, the instantaneous power measurements are processed through a low-pass filter, converting them into their average equivalents. This filter functions as virtual inertia, represented by the term $\frac{1}{m\omega_c}$, introducing a time constant $\frac{1}{\omega_c}$ to the droop control. This adjustment slows the system response slightly, mimicking the behavior of physical inertia. Additionally, the low-pass filter in the control system provides an effect similar to that of virtual damping and is designed to mitigate frequency fluctuations in the MG. The improved filter transfer function to enable ripple-free active and reactive powers is discussed in (Eskandari et al., 2019; Li & Nejabatkhah, 2014).

$$H(s)=\frac{\omega_c}{s+\omega_c}\cdot\frac{s^2+2\zeta_1\omega_n s+\omega_n^2}{s^2+2\zeta_2\omega_n s+\omega_n^2} \tag{39}$$

Where: ω_n is the nominal frequency setpoint and where ζ_1 and ζ_2 are the notch parameters of the improved design of the filter.

The suggested filtration technique enhances the quality of power components by removing fluctuations. Additionally, it increases the transient response of the system. However, challenges such as accurate power distribution and harmonics caused by nonlinear loads remain unresolved.

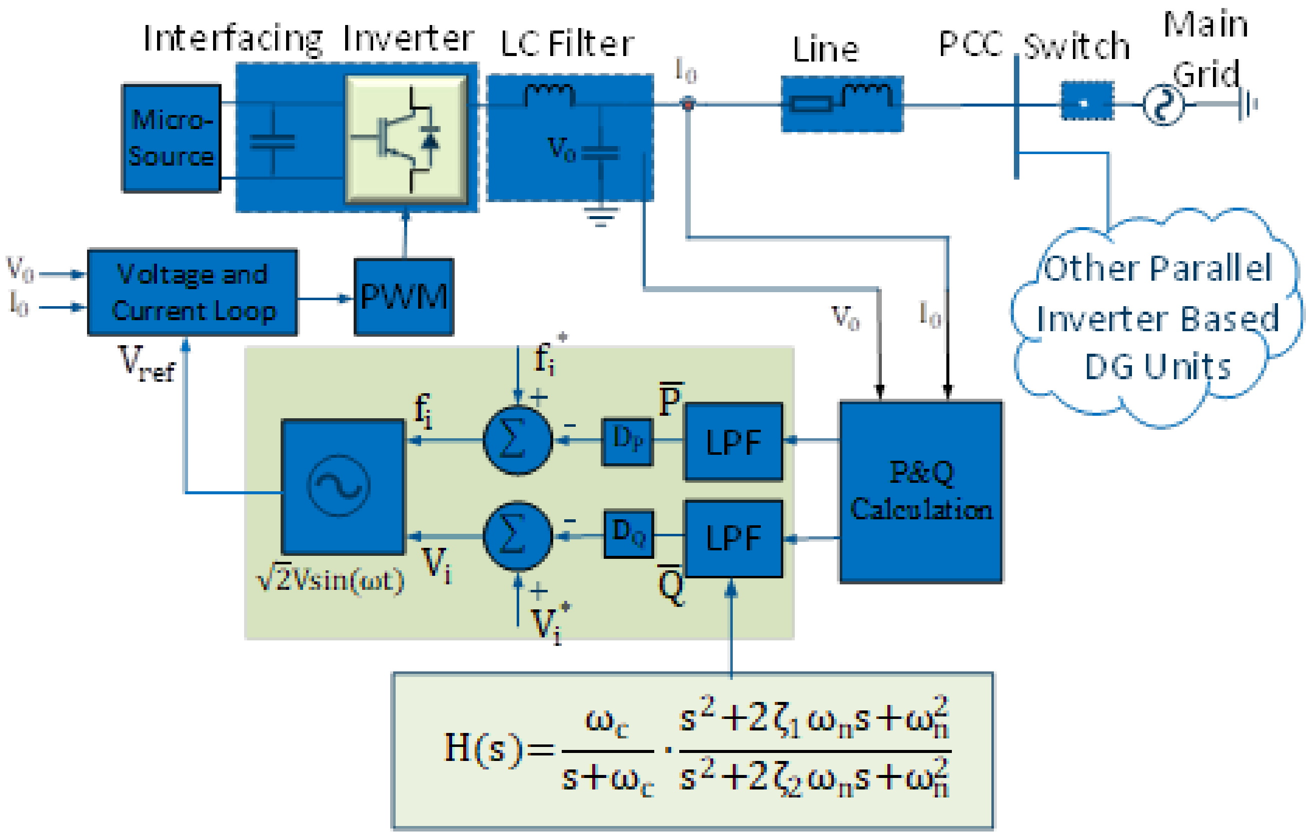

Figure 11 Block diagram of the TDC with a low-pass filter.

3.3.5. Summary of advanced droop control strategies

This section discusses the advantages, disadvantages and concept of modified droop controllers in tabular form in Table 2.

3.3.6. Virtual synchronous machine (VSM)-based control

Conventional power systems rely on the inertia of synchronous generators to maintain grid stability during load fluctuations. However, renewable sources such as solar and wind sources lack such inertia, as they connect to the grid via static power electronics converters without mechanical inertia.

As DG units with low inertia become more common, the MG frequency may vary too quickly under load disturbances, such as the start-up or disconnection of high-power induction motors, resulting in frequency swings.

To address the issue of inertia, the VSM has been suggested as a method to offer extra inertial support via distributed generators that have static power electronic converters (Beck & Hesse, 2007; D' Arco & Suul, 2013; "Synchronverters: Grid-Friendly Inverters That Mimic Synchronous Generators," 2012; Zhong & Weiss, 2011).

Table 2 Summary of communication-independent modified droop PSCs.

Control Method	Concept/Improves TDC on	Advantages	Disadvantages
Virtual P-Q Frame Structure Transformation	Decouples active and reactive power via virtual frame. Problem Addressed: Strong P-Q coupling in mixed impedance lines causing inaccurate power sharing.	Simplified control, decouples P and Q, enhancing power sharing accuracy.	Variability in virtual transformation angle can cause issues. Implementation complexity; requires virtual frame transformation.
Virtual ω-V Frame Structure Transformation	Decouples active and reactive power via virtual frame Problem Addressed: Addresses TDCs poor handling of impedance mismatches and power sharing inaccuracies.	Facilitates independent control of active and reactive power, improving stability.	Variations in virtual transformation angle can cause impedance mismatches and disrupt synchronization.
(P-Q). f/(P+Q). V	Incorporates line impedance characteristics for power sharing. Decouples active and reactive power in mixed impedance lines. Problem Addressed: TDCs inability to effectively decouple active and reactive power in mixed impedance lines	accurately shares power in MV MGs Improves voltage regulation;	Complex control strategy Detailed line impedance knowledge needed.
P-f/Q-V dot	Introduces a voltage restoration loop to stabilize voltage over time. Problem Addressed: Reactive power sharing challenges due to line impedance in TDC.	Improves reactive power independence Stabilizes voltage fluctuations	Sensitive to initial system conditions Steady-state solution may not exist Easy to destabilize
Virtual Impedance Method	Simulates line impedance for improved power sharing. Problem Addressed: Addresses inaccurate reactive power sharing due to mismatched impedances.	Enhanced stability accurate power sharing Harmonic power sharing possible with its variants	Increased control complexity, challenges in transient response and voltage regulation.
Droop with Lowpass Filter	Emulates inertia and damping through lowpass filtering of power signals to damp low frequency oscillations. Problem Addressed: frequency excursions caused by lack of physical inertia and damping in static converter-based MGs.	Damps low frequency oscillations using virtual inertia and damping Mimics physical response of synchronous generators Enhanced transient response	Challenges with nonlinear loads and harmonics Virtual inertia may not perfectly replicate the characteristics of physical inertia
Arctan Droop	Incorporates an arctan function to provide a nonlinear response to power changes Problem Addressed: Linear droop's inflexibility in response to large power deviations and limited frequency bounding.	Provides a nonlinear response, allowing for a wider frequency bounding range Softer response for large power deviations	May require fine-tuning of the arctan function parameters
Angle Droop Controller	Manages real power sharing in highly inductive networks. Problem Addressed: Addresses Challenges faced by TDC with phase alignment and synchronization.	Constant Frequency regulation	Required GPS signals, Timing discrepancies can lead to instability.
Virtual Flux Droop (VFD) Control	Adjusts the virtual flux instead of output voltage for power sharing. Problem Addressed: Addresses TDCs limitations with steady-state frequency deviation and transient voltage regulation.	Low steady-state frequency deviation Improved voltage regulation during transients.	Requires precise control and may struggle with rapid load changes or system disturbances, inaccurate reactive power sharing accuracy.

P-Q-V Droop Control	Voltage regulation at PCC while controlling P and Q. Problem Addressed: Poor voltage regulation at PCC	Directly regulates voltage at PCC; Manages P and Q simultaneously.	Depends on lookup table for droop coefficients; complex real-time adjustment needed.

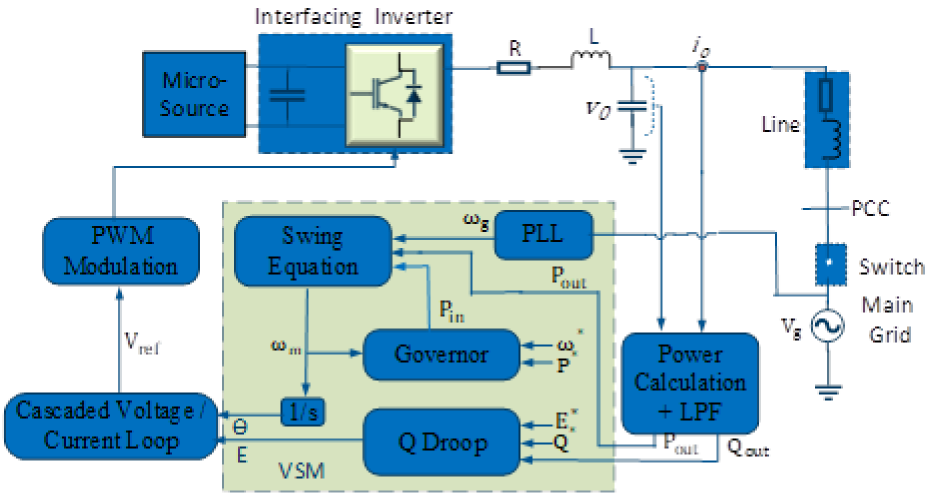

Figure 12 Block diagram of the virtual synchronous machine. *Source:* Hu et al., (2022).

VSM and droop control both emulate synchronous generators; however, VSM incorporates virtual inertia through the swing equation, whereas droop control adjusts only active and reactive power (Liu et al., 2016). This distinction is particularly crucial for handling critical loads in islanded MGs. The block diagram of the VSM is depicted in Figure 15 (Hu et al., 2022).

The virtual shaft power determined by the governor, denoted by P_{in}, is adjusted on the basis of the product of the difference between the virtual rotor angular frequency (ω_m) and the nominal angular frequency (ω^*) and the droop coefficient D_{VSM}. This relationship emulates how a governor in a traditional synchronous generator responds to changes in frequency by adjusting the input mechanical power.

$$P_{in} = P^* - D_{VSM}(\omega_m - \omega^*) \tag{40}$$

The swing equation from classical power system dynamics, which relates the rate of change of the angular frequency ($\frac{d\omega_m}{dt}$) to the difference between the input and the measured output power P_{out}, is applied to the VSM with virtual inertia J and damping factor D to emulate the rotor inertia. ω_g is the grid angular frequency. This reflects the generator's physical response to power imbalances.

$$P_{in} - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g) \tag{41}$$

By integrating the governor equation into the swing equation [89], a comprehensive dynamic model of the VSG is established, capturing both the droop control response and the inertial response.

$$P^* - D_{VSG}(\omega_m - \omega^*) - P_{out} = J\omega_m \frac{d\omega_m}{dt} + D(\omega_m - \omega_g) \tag{42}$$

Under the assumption that the virtual inertia J and damping D are zero, the equation simplifies to a direct relationship between the measured angular frequency ω_m and the output power P_{out}, akin to conventional droop control without inertia.

$$\omega_m = \omega^* + \frac{P^* - P_{out}}{D_{VSM}} \tag{43}$$

The examination reveals that conventional droop control is essentially a subset of the VSM approach. Specifically, when the droop coefficient (D_{VSM}) is set as the reciprocal of the virtual inertia ($1/D_P$), traditional droop control is derived from the VSM. Figure 18 shows the concept, advantages and disadvantages of VSM control.

Efforts in research have focused on integrating the VSM approach into power converter control to improve system stability and power balance. For example, a virtual inertia-based scheme to regulate voltage and frequency stability was proposed in (Natarajan & Weiss, 2017; Zhong & Weiss, 2011). An adaptive inertial method for improved dynamic frequency regulation using the adaptive inertial method (Hou et al., 2020) and the VSM-based self-tuning algorithm [92] is investigated in detail. Reference (Liang et al., 2021) proposed the application of a VSM within a low-voltage network, where virtual impedance was introduced to make the overall line impedance inductive. VSM control struggles with renewable energy variability; mere tweaks to inertia and damping are not always effective for frequency stability. The solution offered is an MPC-VSM strategy, which enhances the system frequency and voltage stability (Long et al., 2021). A model predictive control-based strategy for managing the frequency of the electrical grid by considering electric vehicles (EVs) at charging stations (CSs) as a controllable load was discussed in (Ke et al., 2024). An adaptive virtual inertia strategy to provide ancillary services such as improved frequency regulation and voltage support to an AC/DC MG was proposed in (Rokrok & Golshan, 2010).

3.3.7. Adaptive droop control strategies

Adaptive droop control strategies represent an evolution of traditional droop methods aimed at overcoming their inherent limitations in DG systems and MGs. These strategies enhance power sharing, voltage regulation, and system stability by dynamically adjusting droop control parameters on the basis of real-time operating conditions. Adaptive droop control is particularly significant in systems with high penetration of renewable energy sources, where variability and uncertainty demand robust, flexible, and responsive control techniques. The following section discusses various adaptive droop methods, their operational principles, mathematical formulations, and performance advantages in both islanded and grid-connected MGs.

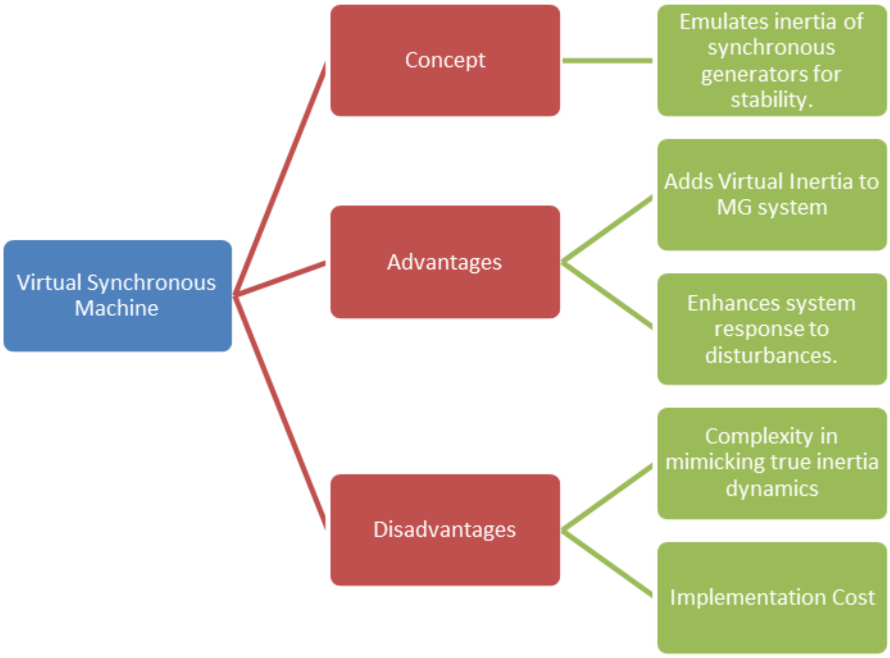

Figure 13 Summary of virtual synchronous machine control.

3.3.7.1. Adaptive voltage regulation droop control

Kim et al. (2002) proposed a novel adaptive voltage regulation droop control method that adaptively adjusts the reference voltage of each converter module. This is achieved by monitoring the reactive power drawn from each DG inverter module and adjusting the reference voltage to improve both voltage regulation and reactive power sharing performance. In this technique, the maximum reactive power ($Q_{i,max}$) drawn from each unit is stored and compared with the reference set values (Q_i^*) of the reactive power.

When the reactive power (Q_i) is below the reference value (Q_i^*), *the* $Q_i < Q_i^*$, control action is as per the standard droop equation given below.

$$V_i = V_i^* - D_{Qi}(Q_i - Q_i^*) \tag{44}$$

When: Q_i exceeds a threshold reference Q_i^*, $Q_{i,max} > Q_i^*$, to avoid overloading the DG inverter, the adaptive droop control method reduces the inverter's output voltage proportionally to the amount by which the output reactive power exceeds the setpoint. The equation represents this as an additional term involving D_k, which is a gain factor.

$$V_i = V_i^* - D_{Qi}Q_i - D_k(Q_i - Q_i^*) \tag{45}$$

Figure 19 shows the operational mechanism of this method. Before the reactive power Q_i exceeds Q_i^*, the output voltage follows lines #1 and #2. When the reactive power exceeds Q_i^*, the output voltage follows lines #1' and #2'. If Q_i decreases below Q_i^* again, the output voltage follows lines #1'' and #2'' instead of lines #1 and #2 because D_k is stored and subtracted constantly.

The method's success is attributed to its adaptive control of the reference voltage, which optimizes performance without the need for complex interconnections or communication between modules.

3.3.7.2. Adaptive nonlinear voltage droop controller

By selecting suitable parameters, the proposed strategy in (Rokrok & Golshan, 2010) achieves excellent voltage regulation. The standard frequency droop method meets key operational goals: efficient active power distribution, effective reactive power sharing, and stable voltage control.

This technique compensates for the feeder impedance drop by adding the terms in the voltage droop control by taking into account the impact of both the active power (P) and the reactive power (Q) drawn from a DG inverter, as well as the impedance of the connecting lines on the voltage at the bus. The modified E-Q droop equation, which incorporates terms to compensate for voltage drops across connecting impedances, improves voltage regulation and reactive power sharing, is given as:

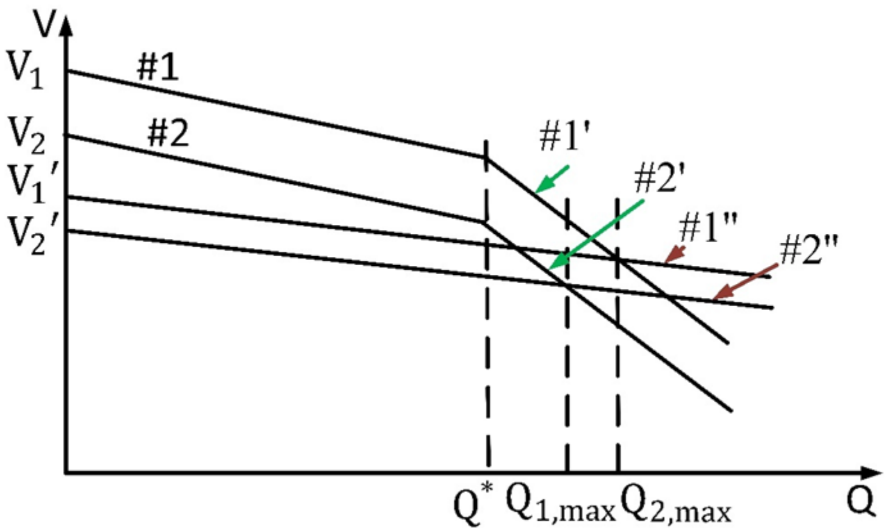

Figure 14 Operational mechanism of adaptive droop control.

$$E_i = \left(V_i^* + \frac{r_i}{V_i^*}P_i\right) - \left(D_{Qi} - \frac{x_i}{V_i^*}\right)Q_i \tag{46}$$

It is evident from the equation that the nominal voltage amplitude is increased by $\frac{r_i}{V_i^*}P_i$ and that the droop coefficient D_{Qi} is reduced by $\frac{x_i}{V_i^*}$. This adaptation reduces the droop slope and introduces an additional component to V_i^*. The term $D_{Qi}Q_i$ is subtracted from the adjusted reference voltage to account for the conventional voltage droop due to reactive power. This ensures that the VSC's voltage decreases with increasing reactive power output to maintain power balance and stable operation within the MG.

The nonlinear function defining the voltage adjustment to account for the reactive and active power outputs and enhancing system stability and efficiency under varying load conditions is given as

$$E_i = E_i^* - D_i(P_i, Q_i) \cdot Q_i + \left(\frac{r_iP_i}{E_i^*} + \frac{x_iQ_i}{E_i^*}\right) \tag{47}$$

$$D_i(P_i, Q_i) = n_{qi} + k_{qi}\,{Q_i}^2 + k_{pi}\,{P_i}^2 \tag{48}$$

Where: $D_i\,(P_i, Q_i)$ is a function that defines the droop control strategy on the basis of the DG inverters' power outputs and includes terms that allow for the adaptation of the droop characteristic to different power output levels. k_{qi} and k_{pi} are droop coefficients.

Multiobjective optimization is used to balance voltage regulation, and the reactive power sharing and performance of the method are evaluated on the basis of the circulating reactive power and load voltage deviations.

3.3.7.3. Adaptive droop control based on integral and derivative terms

1. Derivative term-based adaptive droop: In small-scale AC MGs, significant load variations are common and can impact system stability. To address this, the adaptive derivative term method proposed in (Chung et al., 2010; Kim et al., 2011; Mohamed & El-Saadany, 2008) introduces a combination of static and transient droop gains. This approach is designed to

enhance the damping of low-frequency oscillations, which are crucial for maintaining stable power sharing and improving the system's dynamic response. The transient droop gains, represented as D'_P and D'_Q, are specifically implemented to mitigate fluctuations in power distribution among the DG units. The corresponding control equations are formulated as follows:

$$f_i = f^* - D_{pi}(P_i - P_i^*) - D'_P \frac{dP_i}{dt} \tag{49}$$

$$V_i - V^* = -D_{Qi}(Q_i - Q_i^*) - D'_Q \frac{dQ_i}{dt} \tag{50}$$

Once the system has settled to its new equilibrium after a transient, derivative terms no longer influence the control output; hence, they are valid only for the dynamic behavior of the system. They are not used under steady-state conditions. By integrating a derivative term into standard droop control, it effectively mitigates power fluctuations.

1. Derivative and Integral Terms-Based Adaptive Droop: A mode adaptive droop control strategy to enhance the performance of the controller in (Mohamed & El-Saadany, 2008) is suggested in (J. Kim et al., 2011), which can be operated in grid-connected and islanding modes of operation. It improves the power factor in grid connected mode by using an integral term present in the reactive power droop equation and power sharing dynamics in islanding mode via a derivative term. The droop equations are given as

$$f_i = D_{pi}(P_i - P_i^*) + D_i \frac{d(P_i - P_i^*)}{dt} \tag{51}$$

$$V_i = D_{Qi}(Q_i - Q_i^*) + D_j \int (Q_i - Q_i^*)\, dt \tag{52}$$

2. Adaptive transient droop control: A technique to damp power oscillations, improve transient performance and eliminate the circulating current under all operating conditions was suggested in (Hassanzahraee & Bakhshai, 2012). The governing equations are given as

$$f_i = f_i^* - D_{kpi}P - D_{pim}\frac{dP}{dt} + D_{Qim}\frac{dQ}{dt}, \tag{53}$$

$$V_i = V_i^* - D_{kqi}Q + D_{pin}\frac{dP}{dt} - D_{Qin}\frac{dQ}{dt} \tag{54}$$

3.3.7.4. Adaptive P–δ droop control strategies

The adaptive P–δ/Q–V strategy combines traditional droop control (TDC) for power sharing with an adaptive supplementary controller to enhance stability and dynamic performance, especially in high-RES systems (Majumder, Chaudhuri, et al., 2010; Seema P. Diwan & Rajin M. Linus, 2024). While higher droop gains improve load sharing among DG units, they also increase sensitivity to disturbances. The supplementary controller addresses this by maintaining stability even under high droop conditions.

The control equations are as follows:

$$\delta_i = \delta_i^* = -D_{Pi}\,(P_i - P_i^*) + \Delta\delta_i \tag{55}$$

$$V_i - V_i^* = -D_{Qi}(Q_i^* - Q_i) + \Delta V_i \tag{56}$$

Where: $\Delta\delta_i$ and ΔV_i are the voltage magnitude and voltage angle correction by the adaptive controller, respectively.

The block diagram of the control structure is depicted in Figure 20. The controller's parameters, such as gains and time constants, are optimized to ensure stability and accommodate the range of operating conditions.

3.3.7.5. Adaptive droop with frame transformation

Reference (Vasquez et al., 2009) presents a novel adaptive droop with a frame transformation control strategy for DG inverters that allows for both islanded and grid-connected operations. The strategy adapts to system changes and uses frame transformation for decoupling active and reacive powers.

The DG inverter output powers P_i and Q_i are decoupled from the grid impedance and transformed into novel variables (P_{ci} and Q_{ci}). The droop control equations for phase angle control and voltage magnitude control are given as

$$\delta = -G_p(s)Z_g\left[(P_i - P_i^*)\sin\theta_g - (Q_i - Q_i^*)\cos\theta_g\right] \tag{57}$$

$$V = V^* - G_q(s)Z_g\left[(P_i - P_i^*)\cos\theta_g + (Q_i - Q_i^*)\sin\theta_g\right] \tag{58}$$

Active and reactive power decoupling is accomplished via orthogonal frame transformation. where $G_p(s)$ and $G_q(s)$ are the transfer functions for the droop control of the active power and reactive power, respectively, Z_g is the grid impedance, and θ_g is the phase angle of the grid impedance. V^* is the amplitude voltage reference, which takes the values of the estimated grid voltageV_g.

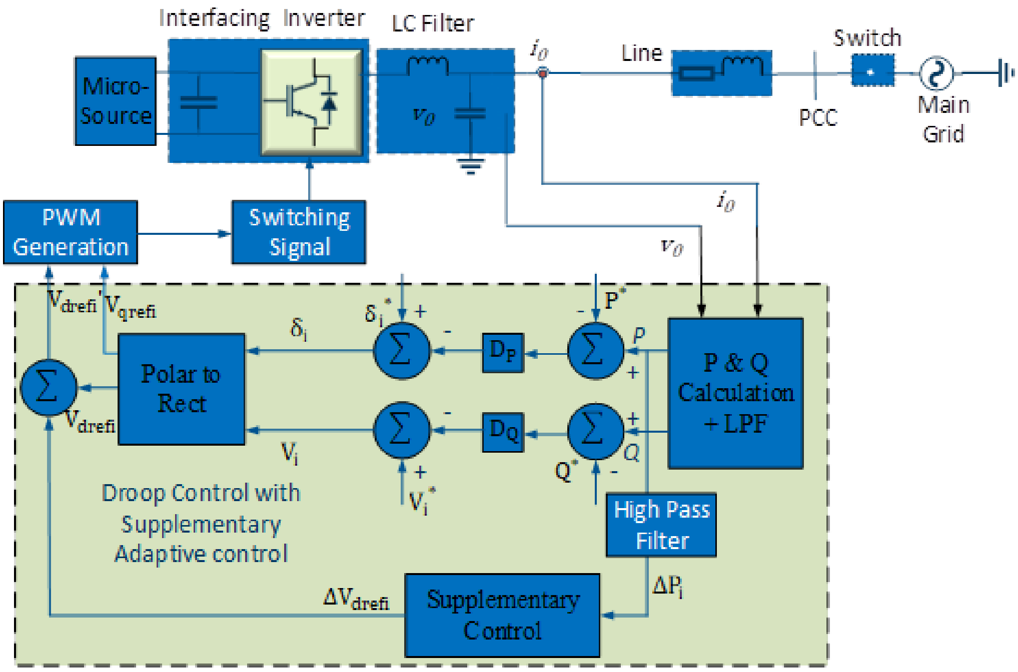

Figure 15 Block diagram of adaptive P- δ/Q-V control.

The design of controllers allows for dynamic adjustment of the DG inverter output in response to changes in power demand or other system conditions. The transfer function of the controller is given as

$$G_p(s) = \frac{m_i + m_p s + m_d s^2}{s} \tag{59}$$

$$G_q(s) = \frac{n_i + n_p s}{s} \tag{60}$$

The block diagram is depicted in Figure 21. This method allows independent and accurate active and reactive power injection to the grid with improved dynamics decoupled from the grid impedance magnitude and phase, hence improving overall stability.

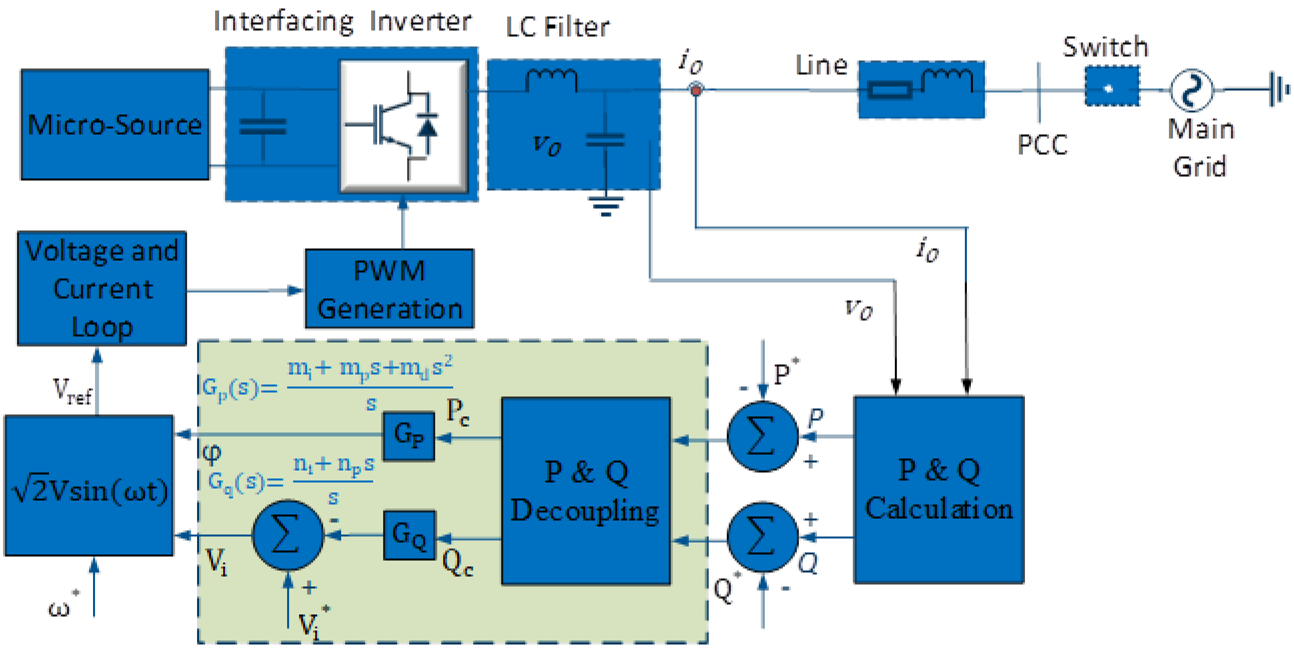

Figure 16 Block diagram of adaptive FT-based droop control.

3.3.7.6. Adaptive virtual flux droop (AVFD) control strategy

The AVFD control strategy introduced in (Khanabdal et al., 2022) is a modification of the VFD method to address issues arising from unequal feeder impedances, which can often result in uneven power sharing among DG units.

The AVFD control strategy incorporates the idea of virtual impedance to mitigate the effects of mismatched line impedances, enabling accurate power sharing proportional to the ratings of the sources, despite line impedance mismatches.

The control equations are given as (Khanabdal et al., 2022).

$$\delta_i = \delta_i^* - D_{Pi}(P_i^* - P_i) - k_{ip}\int (P_i - P^*)dt \quad (61)$$

$$|\psi_i| = |\psi_i^*| - D_{Qi}(Q_i^* - Q_i) - k_{iq}\int (Q_i - Q^*)dt \quad (62)$$

Where: k_{ip} and k_{iq} are compensatory coefficients for active and reactive powers, respectively, and where P^* and Q^* are the active power and reactive power setpoints received from the energy management system of secondary control. The terms $k_{ip}\int(P_i - P^*)dt$ and $k_{iq}\int(Q_i - Q^*)dt$ account for long-term correction over real power imbalances and reactive power errors accumulated over time, and $D_{Pi}(P_i^* - P_i)$ and $D_{Qi}(Q_i^* - Q_i)$ account for the immediate droop response.

The block diagram in Figure 22 illustrates the addition of integral control loops to manage the active and reactive power in the system (Khanabdal et al., 2022). The AVFD indirectly offsets the issues caused by mismatched line impedances via the compensatory terms in equations (80) and (81), which mimic the impact of a theoretical virtual impedance. This technique ensures a precise power distribution that aligns with the capacities of the different power sources.

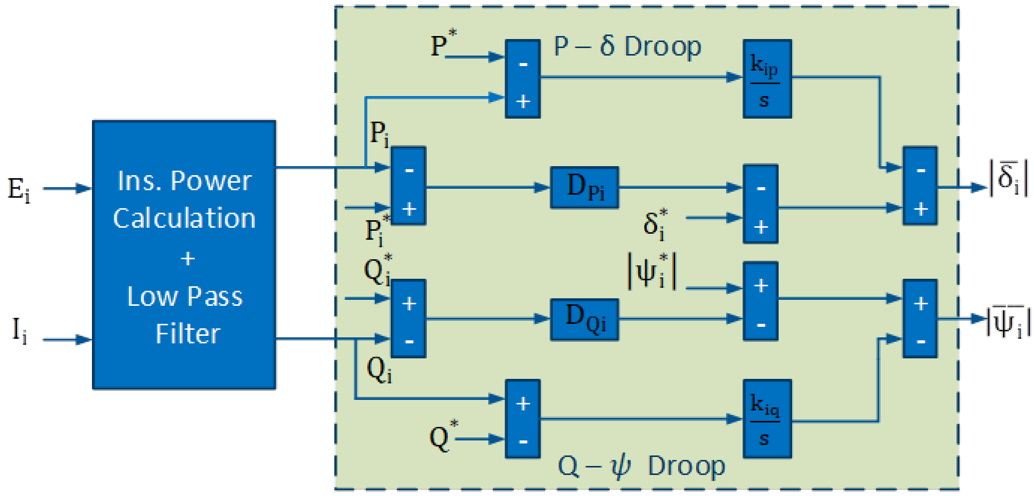

Figure 17 Block diagram of adaptive virtual flux droop control. *Source:* Diwan & Linus (2024).

3.3.7.7. Adaptive virual impedance-based droop methods

The control scheme proposed in (Ahmed et al., 2022) introduces an innovative method to improve power sharing accuracy among DG units by modifying the inverter's output impedance. As discussed in (Diwan & Linus, 2024), this is achieved by continuously monitoring the difference in active and reactive power flow between the inverter terminal and the point of common coupling (PCC). By dynamically adjusting the output impedance based on this power transfer difference, the inverter can better match the desired power sharing characteristics, particularly under mismatched line impedance conditions or unbalanced loading. This approach enhances the voltage regulation and overall stability of the MG while maintaining proper coordination among multiple DG units. Furthermore, it supports both grid-connected and islanded operation modes, making the scheme suitable for flexible and resilient microgrid applications.

Extensive research has been devoted to implementing adaptive virtual impedance (VI)-based strategies for enhancing the functionality of MGs; For instance, (Vijay et al., 2021) proposed a decentralized adaptive control using VI proportional to DG output current to mitigate impedance mismatch effects. Under high X/R ratios, standard droop control enables real power sharing but leads to uneven reactive power distribution; at low X/R ratios, reverse droop ensures reactive power sharing, compromising real power distribution.

In (Liu et al., 2019), an adaptive virtual impedance control strategy to enhance power sharing in islanded MGs and to address unbalance and harmonics without the need for a communication network was proposed. It is based on the injection of an extra small AC signal (SACS) in the output voltage of each inverter. The advantage of this method is that it achieves accurate active, reactive and harmonic power sharing without using communication links and prior knowledge of system parameters.

In (Mahmood et al., 2015), a strategy to improve the accuracy of reactive power sharing in an islanded MG by employing adaptive virtual impedances was discussed. This strategy uses communication to adjust virtual impedances and compensate for the mismatch in feeder impedances.

Other studies (Guerrero et al., 2007; Rowe et al., 2013; Yao et al., 2000) used fixed resistive, inductive, or complex impedances to improve sharing accuracy but required precise feeder impedance estimation. (Wei et al., 2019) proposed an adaptive VI method based on deviations from average DG active power, suitable for parallel MGs. In contrast, approaches by (Eskandari et al., 2020; Hoang & Lee, 2018) achieved accurate reactive power sharing without feeder knowledge but relied on high-bandwidth communication.

Finally, (Baghaee et al., 2018; Baghaee et al., 2018) used line current and PCC voltage feedback with a neural network-based controller to improve sharing under unbalanced and nonlinear loads, though at the cost of computational complexity.

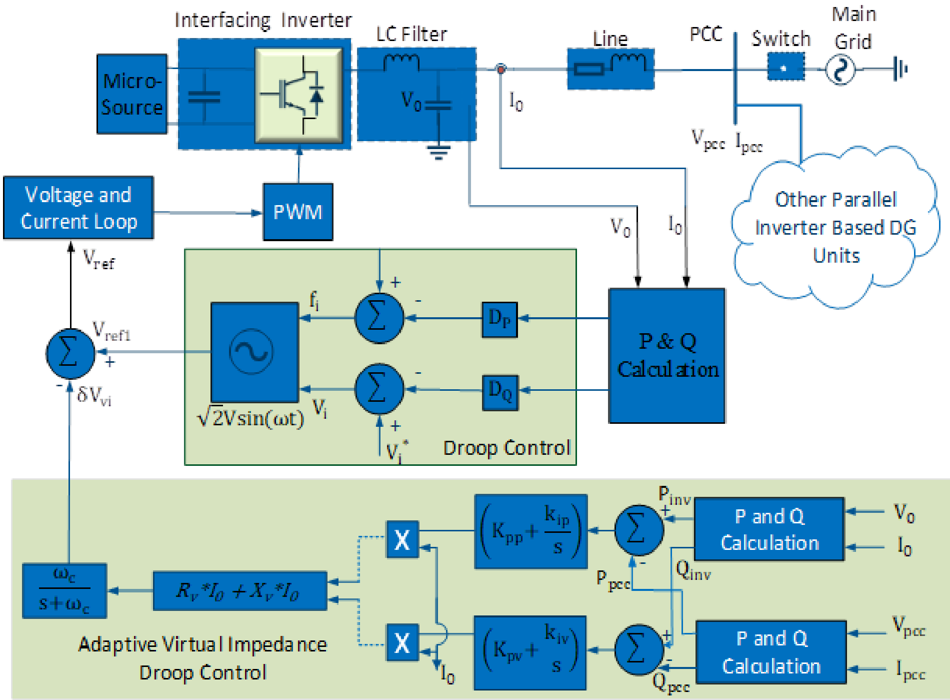

Figure 18 Block diagram of the adaptive virtual impedance droop control method.

3.3.7.8. Summary of adaptive droop control methods

This section summarizes the advantages, disadvantages and concepts of adaptive droop-based methods discussed earlier.

4. Advanced Control Techniques

MGs have advanced significantly with the integration of RES, ESS, and diverse loads, but these advancements have also introduced challenges that classical control techniques struggle to address.

Conventional methods often fail under distorted or imbalanced conditions and weak grid connections, as they are unable to counteract uncertainties originating from the upstream grid effectively. Similarly, these approaches are unable to effectively address the influence of line impedance on power-sharing precision, particularly in low X/R ratio scenarios, where droop-based techniques and PI control loops have limitations. Additionally, the nonlinear and uncertain nature of MG loads, which are often topologically unknown and parametrically variable, introduces dynamics that classical controllers cannot model accurately. Another major limitation is the lack of flexibility in shaping the impedance of grid-forming (GFM) and grid-following (GFD) voltage source converters, which require different impedance characteristics for stable operation under varying grid conditions.

To overcome these limitations, robust and advanced control techniques have become essential. These methods, including adaptive and robust control strategies, provide the flexibility to dynamically adjust to changing system and environmental conditions, ensuring consistent performance and resilience. Table 4 shows the comparison between conventional controllers and robust controllers. These techniques are discussed in the following section.

Table 3 Summary of adaptive droop control methods.

Control Method	Concept/Improves TDC on	Advantages	Disadvantages
Adaptive Virtual Flux Droop (AVFD) Control	Adjusts virtual flux for power sharing, incorporating virtual impedance for mismatch compensation. Problem Addressed: Addresses power sharing issues due to mismatched line impedances.	Accurate power sharing proportional to DG ratings; mitigates mismatch impacts	Complex control strategy; potential challenges with rapid system changes.
Adaptive Dynamic Voltage Regulation Droop	Monitors reactive power to adjust reference voltage of converter modules. Problem Addressed: Addresses TDCs inability to manage voltage fluctuations due to varying reactive power.	Enhances voltage stability and reactive power sharing.	Increased system complexity and dependency on accurate reactive power monitoring.
Adaptive Nonlinear Voltage Droop Control	Adjusts voltage droop control taking into account both active and reactive power impacts. Problem Addressed: Challenges with voltage regulation and reactive power sharing due to line impedance.	Improved voltage regulation and effective reactive power sharing. Power sharing under heavy load conditions	Requires careful parameter selection for optimal performance. System parameters should be known in advance.
Adaptive Droop Control based on Derivative Integral Terms	Incorporates static and transient droop gains to stabilize low-frequency modes and improve system dynamics. Problem Addressed: Static nature of traditional droop fails to compensate for fluctuating loads and varying line impedances.	Stabilizes power sharing and enhances dynamic response of the system.	Complex control strategy, requiring tuning of derivative and integral terms. The magnitude and phasor angle of output impedance is difficult to control because the virtual reactance is too dependent on voltage bandwidth
Adaptive P–δ/V–Q Droop	Uses TDC with supplementary adaptive control for enhanced stability and dynamic response. Problem Addressed: Sensitivity to disturbances and instability due to high droop gains.	Ensures system stability with high droop gains, responsive to rapid power changes.	Necessitates additional control actions, potential complexity in control implementation.

4.1. Robust H∞ control

The aim of H∞ control is to minimize the impact of uncertainties and disturbances on the transient and steady-state performance of a system. This approach is based on synthesis techniques to achieve robust performance or stabilization of multivariable linear systems. For nonlinear systems, robustness is achieved in the state space by solving the Riccati equation or utilizing linear matrix inequalities (LMIs). In MG applications, robust H∞ controllers have been proposed to handle external disturbances and model uncertainties, ensuring system stability and performance (Sedhom et al., 2020). For hybrid AC/DC MGs, a multivariable H∞ control method is applied to regulate the frequency in islanded modes, considering uncertainties in the state of charge (SOC) of energy storage systems (Lam et al., 2020). The LMI-based approach ensures robustness under such conditions. Moreover, robust H∞ controllers address unmodeled dynamics through constraints such as regional pole placement, which enhances the transient response, and H∞ synthesis, which reduces the control effort while maintaining accurate tracking of reference commands for distributed generation (DG) output voltages (Raeispour et al., 2021). These controllers ensure reliable operation even in the presence of significant challenges, making them effective tools for robust control in MG system.

4.2. Sliding mode control (SMC)

SMC is a nonlinear control technique tailored to enhance robustness against variations in parameters, noise, and external disturbances, proving particularly effective for dynamic systems such as MGs. The core concept of SMC involves defining a sliding surface or hypersurface in the state space that represents the desired system behavior. The control law ensures that the system trajectory reaches and remains on this surface, achieving stability and robustness even in the presence of uncertainties. This method is especially valuable in nonlinear and uncertain environments where traditional control techniques, such as proportional–integral (PI), proportional resonance (PR), and predictive deadbeat (DB), often fail to perform effectively.

Table 4 Comparison of conventional and robust controllers.

Characteristic	Conventional Controller	Robust Controller
Complexity	Simple	Complex
Robustness	Low	High
Scalability	Moderate	High
Adaptability	Low	High
Gain	Fixed	Dynamic
Reliability	Low	High
Optimal Operation	Not guaranteed	Guaranteed
Dependency on System Dynamics	More	Less

SMC has been extensively SMC has been extensively studied as a robust nonlinear control technique to ensure stability in the presence of parameter constraints. A decentralized SMC approach is used to improve stability, power sharing, and system robustness in MGs with nonlinear and unbalanced loads (Baghaee et al., 2024; Cucuzzella et al., 2017). Additionally, SMC-based control strategies have been developed to ensure fault ride-through (FRT) performance in GFM inverters, allowing secure operation during transient disturbances (Eskandari & Savkin, 2021). Moreover, SMC has also been applied to manage positive-sequence voltage and power, whereas fractional-order techniques and Lyapunov theory handle negative-sequence currents and harmonics, ensuring stable performance under challenging conditions (Delghavi et al., 2016).

SMC offers several advantages, including its robustness against parameter variations and external disturbances, scalability through decentralized control, and the ability to achieve fast responses. It is also highly flexible and capable of addressing both deterministic and nondeterministic uncertainties. However, challenges such as chattering, i.e., high-frequency oscillations near the sliding surface and the complexity of implementation, remain significant drawbacks. To mitigate these issues, improvements such as continuous or smooth switching functions, fractional-order SMC, and Lyapunov-based design have been introduced, reducing chattering effects and enhancing system performance (Delghavi et al., 2016). Fully decentralized SMC methods have also been developed to eliminate reliance on global system information, further improving scalability and robustness (Zhang & Hredzak, 2019a). Figure 24 shows the block diagram of the sliding mode controller for restoring the voltage and frequency of the MG (Zhang & Hredzak, 2019b). The control coefficients, α_v and β_v, play crucial roles in this process. The parameters p_v and q_v are positive values representing the consensus error orders. Additionally, the control variables $u_i^v, u_i^q, u_i^\omega, u_i^SOC, V_i^ref$ and ω_i^{ref} correspond to the voltage, reactive power, frequency, and SOC control law adjustment. The control laws govern the nominal voltage and frequency of the i[th] DG. The parameter v_{ref} represents the global reference voltage, while V_i^{nom} serves as the control input.
as the control input.

4.3. Backstepping control

The robust backstepping control approach is grounded in the recursive Lyapunov method, which enables systems to operate effectively even under undesirable conditions. This method provides flexibility and robustness by extending the kinematic-level controller to address dynamic scenarios and manage parameter uncertainties. It is widely used in scenarios requiring enhanced resilience against uncertainties and disturbances.

In AC MGs, robust backstepping control is employed to regulate the voltage, maintain power balance, and improve system reliability under challenging conditions. It is specifically used in the following ways: A robust backstepping controller, as proposed in (Dehkordi et al., 2017), is based on the feedback linearization method to maintain power balance and achieve the desired voltage at the PCC. It is robust against parametric uncertainties and external disturbances. A fault-tolerant backstepping controller was used in (Dehkordi & Nekoukar, 2020) to regulate the voltage in the presence of actuator faults and loads with harmonic or interharmonic currents. This approach does not require precise fault or harmonic modeling, enhancing system reliability.

4.4. Impedance shaping

Impedance shaping is a critical control used, particularly for GFM and GFD voltage source converters. It addresses the limitations of conventional PI-based nested control loops, which fail to handle the arbitrary output impedance behavior of these converters under islanded or grid-connected conditions, especially during disturbances or faults. These limitations often lead to instability and cross-coupling between the frequency–power (f–P) and voltage–reactive power (V–Q) loops, significantly affecting the stability and performance of MGs. Impedance shaping ensures that the required impedance characteristics are met under varying operating conditions, enabling decoupling of the f−P and V−Q loops and improving system robustness.

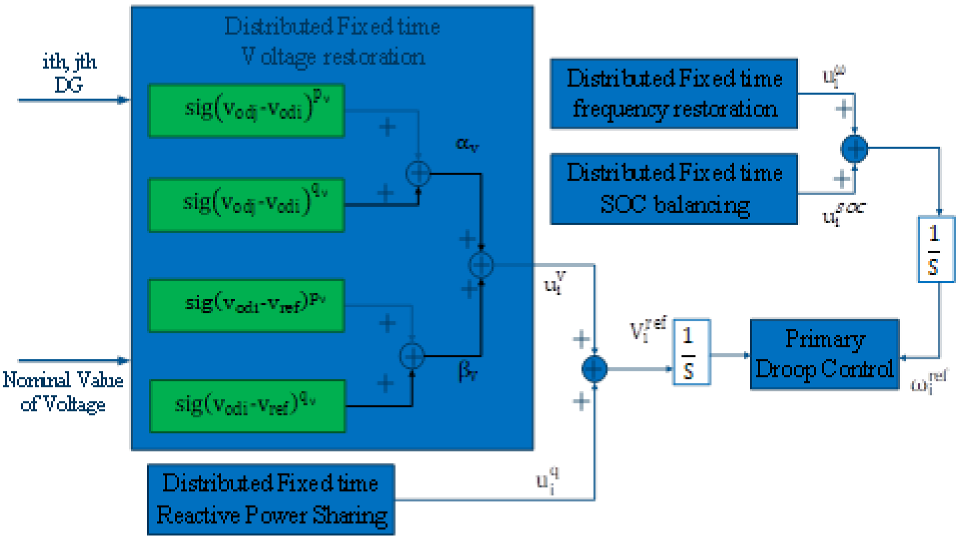

Figure 19 Block diagram of the sliding mode controller for voltage and frequency control in the MG.

Impedance shaping is useful because of its ability to manage challenges such as instability in weak grids, dynamic performance requirements, and high output impedance in GFD converters that hinder power sharing. It also enables MGs to adapt to variable conditions, including seamless transitions between the GFD and GFM modes. A promising solution is the optimal voltage regulator (OVR) (Eskandari et al., 2020), a new control structure based on optimal state feedback control, as shown in Figure 25. The OVR achieves optimal impedance shaping by aligning with power-sharing targets and grid requirements. It operates effectively in both the GFM mode and the GFD mode without requiring a dedicated phase-locked loop (PLL) or structural modifications during mode transitions, showing flexibility and adaptability.

Impedance shaping offers significant advantages, including enhanced stability under disturbances and faults, improved dynamic performance, and optimal functionality in low-voltage and weak grids. However, its implementation poses challenges, such as increased design complexity, increased computational demands, and difficulties in integrating with legacy systems.

5. Artificial Intelligence (AI)

The growing complexity of MG architectures, driven by the integration of IIDGs, has introduced significant challenges that necessitate the adoption of AI in MG control. These challenges include maintaining power quality and stability, managing energy efficiently under varying demand and supply conditions, and developing advanced protection strategies for increasingly intricate systems. Additionally, the rapid fluctuations in demand profiles and the variability of RESs require accurate forecasting and dynamic energy management, tasks that traditional control methods struggle to handle effectively

Operating in both grid-connected and islanded modes further adds to the complexity of MGs, necessitating distinct and flexible energy management and protection strategies. Traditional control systems, which rely heavily on physical models, often fail to adapt to the dynamic and uncertain conditions present in modern MGs. This has led to a growing reliance on AI, which has led to data-driven control approaches capable of addressing real-world complexities without needing detailed system models.

Artificial intelligence (AI), which uses its core functions, i.e., optimization, classification, regression, and data structure exploration, enhances the control and management of MGs.

Optimization is essential for identifying the best solutions from a set of alternatives while adhering to constraints, equalities, or inequalities. In MG control, optimization is widely applied in energy storage system (ESS) management, ensuring efficient charge and discharge cycles to extend the system's lifespan. It also plays a critical role in the optimal dispatch of distributed energy resources (DERs), facilitating resource allocation to meet energy demand while minimizing operational costs and environmental impact. Additionally, optimization is used for fine-tuning control system parameters to enhance the stability, reliability, and performance of MGs under varying conditions.

Classification involves assigning input data to predefined categories or labels, which is particularly useful for anomaly detection and system protection in MGs. For example, classification techniques are used for fault detection and diagnosis, where they help identify and label faults in MG components on the basis of condition monitoring data. Similarly, classification is employed in detecting anomalies in system performance, enabling proactive maintenance and enhancing overall system reliability.

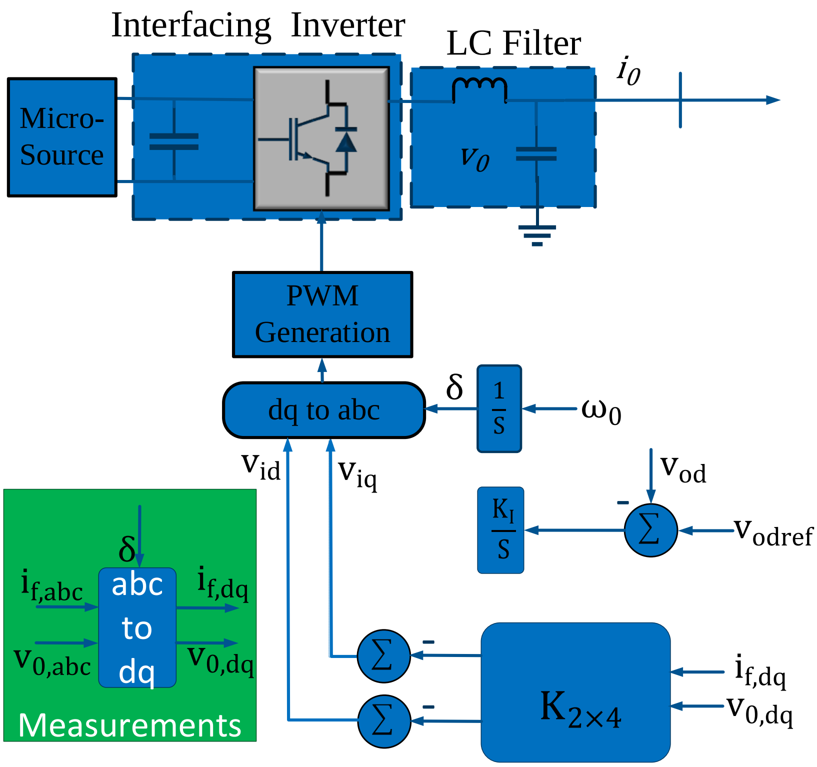

Figure 20 Block diagram of the OVR impedance shaping method.

Regression focuses on predicting continuous target variables by establishing relationships between the input and output variables. In MG control, regression facilitates the development of predictive models that link input signals, such as voltage or frequency, to output control variables, thus enabling intelligent decision-making. It is also critical for forecasting energy consumption patterns on the basis of historical data, which ensures the availability of resources. Additionally, regression is employed in renewable energy prediction, modeling weather-dependent generation, such as solar or wind power, to enhance the integration of renewable energy sources into the grid.

Data structure exploration encompasses clustering, density estimation, and data compression, all of which are crucial for analyzing and interpreting complex datasets in MG control. Clustering is used to group similar data points, such as in the degradation state analysis of MG components or the categorization of load profiles. Density estimation helps identify the distribution of system parameters or load patterns, which provides insights into operational behavior. Data compression reduces the dimensionality of high-dimensional datasets, improving computational efficiency and enabling effective feature extraction. These techniques also support predictive maintenance by clustering degradation states, facilitating optimized maintenance planning.

AI techniques for MG control can be categorized into four main groups: metaheuristic methods, fuzzy logic (FL), expert systems, and machine learning (ML) (Zhao et al., 2021). The following section discusses their application in MG control in detail.

5.1. Metaheuristic methods

Techniques such as genetic algorithms are employed to address optimization problems via high-level problem-solving strategies. These methods excel at finding near-optimal solutions for complex scenarios. Figure 26 shows various optimization techniques that are used for MG applications at the primary level.

The PSO algorithm is one of the most widely used metaheuristic optimization techniques for optimizing the inner loop controllers' parameters. In ACMGs, the authors of (Jumani et al., 2020) reviewed the literature on the application of the particle swarm optimization (PSO) algorithm for dynamic response and power quality enhancement. The PSO algorithm is one of the most widely used metaheuristic optimization techniques for optimizing the inner loop controllers' parameters. Reference (Abbas et al., 2022) presents a modification of the PSO algorithm for the transient response enhancement of the power flow controller in a grid-connected MG. In (Jumani et al., 2018), a Grasshopper optimization algorithm-based controller to optimize the PI controller parameters in an islanded MG was proposed, and its effectiveness was compared with that of other existing algorithms. A modified gray wolf optimization algorithm has also been explored for PI controller tuning in an islanded MG (Almani et al., 2022). The authors in (Vinayagam et al., 2018) employed the PSO algorithm to optimize the PI controllers' parameters of the voltage control loop of the GFM inverter in an islanded MG. The proposed strategy improves the droop control performance by reducing the power and frequency variations, as well as the settling time and overshoot during transient conditions.

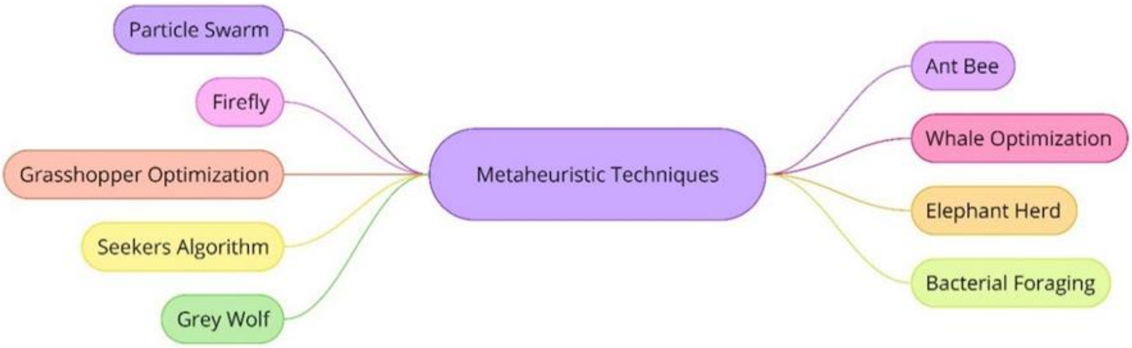

Figure 21 Block diagram of the sliding mode controller for voltage and frequency control in the MG.

5.2. Fuzzy logic (FL)

FL addresses uncertainties within systems by using linguistic variables to simulate human reasoning in decision-making. This approach is particularly useful in scenarios where precise data are unavailable or variability exists (Simoes et al., 1997). In most applications, the fuzzy logic framework comprises four main components (Simoes et al., 1997): fuzzification, rule inference, knowledge base, and defuzzification. During fuzzification, input variables are converted into linguistic terms via membership functions such as triangular, trapezoidal, Gaussian, bell-shaped, singleton, or other customized shapes. The inference module then combines these inputs on the basis of IF–THEN fuzzy rules stored in the knowledge base, which is typically derived from expert knowledge. Defuzzification is the final step, which produces crisp output values from the aggregated fuzzy signals. Fuzzy inference schemes are generally categorized as Mamdani-type (Chen & Bazzi, 2017; Simoes et al., 1997) or Takagi–Sugeno–Kang (TSK)-type (Tseng et al., 2012).

In the Mamdani-type scheme, both the antecedent and consequent membership functions are shape-based, such as triangular functions. In contrast, the TSK-type scheme uses the same antecedent membership functions as the Mamdani-type scheme but represents the consequent membership function as a singleton at constant values. The TSK-type scheme often employs functional membership functions, such as linear or constant types, which increase the accuracy of nonlinear approximations.

Notably, the Mamdani-type scheme typically requires more fuzzy sets for the same task than the TSK-type scheme does. The TSK-type's functional consequent membership functions make it more powerful and precise for complex nonlinear mappings

Owing to the complex dynamics present during the power transfer between the AC and DC buses in hybrid AC/DC MGs, AI-based techniques have been studied to improve the droop control techniques for bidirectional ICs.

An adaptive compensation control strategy based on an adaptive neuro-fuzzy inference system (ANFIS) was introduced in (Ding et al., 2020) to improve reactive power sharing. This strategy uses an artificial neural network (ANN) to optimize the parameters of the fuzzy controller. Specifically, the feedforward neural network (FFNN) algorithm replaces the conventional virtual impedance control loop by learning the transient nonlinear characteristics of the inverter model.

The implemented online ANNs generate virtual compensation voltages v_d^+ and v_q^+ , as illustrated in Figure 27, to minimize the feedback error in the output currents (i_dq) by adapting the neuron weights. This approach enhances system stability and effectively reduces oscillations.

Droop control is typically employed with diesel generators to adjust their power references in proportion to frequency deviations from the nominal value. However, operating diesel generators at maximum capacity is not feasible in certain cases. In (Asghar et al., 2017), it was demonstrated that droop control for diesel generators can be economically replaced with an FL approach combined with a BESS. This FL-based intelligent control technique enhances both frequency and voltage stability. A flow diagram illustrating the proposed control method is presented in Figure 28.

Similarly, a distributed droop control scheme featuring an FL-based voltage–frequency controller was introduced in (Gupta & Paliwal, 2021) to enhance the transition between grid-connected and islanded operations. In (Prasad et al., 2022), a droop control strategy for an ACMG was presented, where droop coefficients were optimized via the elephant herding optimization algorithm to minimize cost. Furthermore, AC subgrids were managed through ANFIS and PID controllers.

As discussed earlier in (Diwan & Linus, 2024), due to the inherently low impedance of power lines in MGs, TDC often fails to ensure accurate power sharing, particularly for reactive power. This inefficiency arises because low line impedance limits the voltage and frequency deviations needed for effective droop operation. To overcome this limitation, (Eskandari et al., 2018) proposed a fuzzy-based consensus control strategy, which introduces intelligent decision-making into the control loop. As illustrated in Figure 29, this method utilizes fuzzy logic to evaluate the local conditions of each DG unit and facilitates coordinated control through a consensus algorithm. By combining fuzzy inference with distributed communication, the control scheme enables better power sharing, improved dynamic performance, and enhanced robustness against parameter variations and uncertainties. This approach is particularly effective in achieving accurate and stable operation in low-impedance networks where conventional methods struggle.

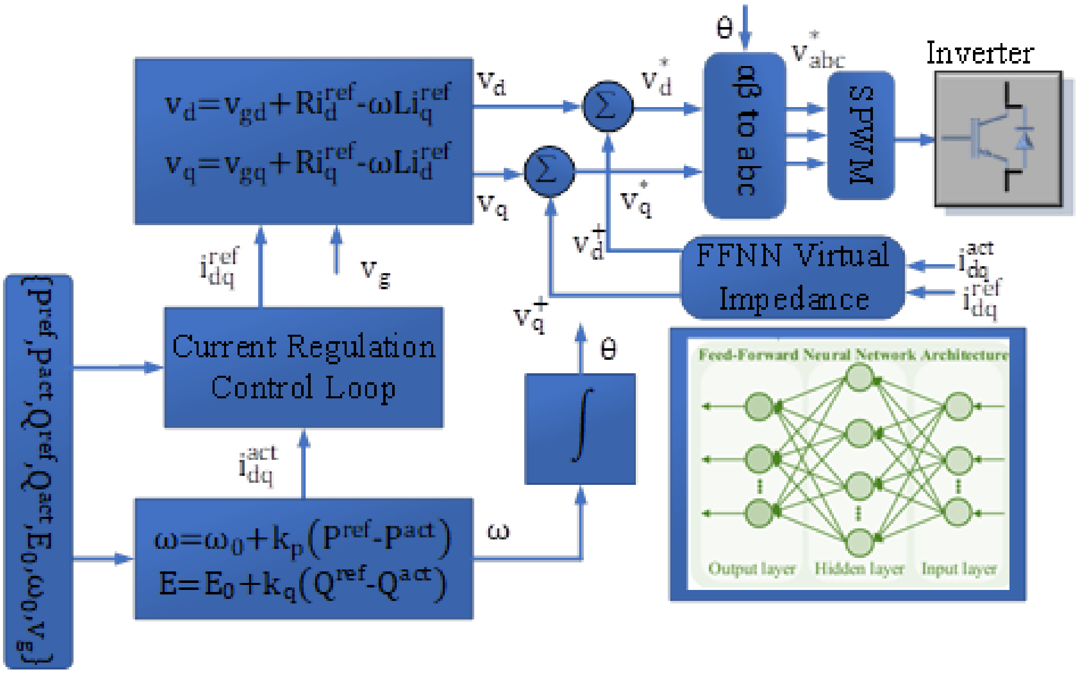

Figure 22 Block diagram of the ANN-based feedforward virtual impedance bidirectional inverter-based microgrid.

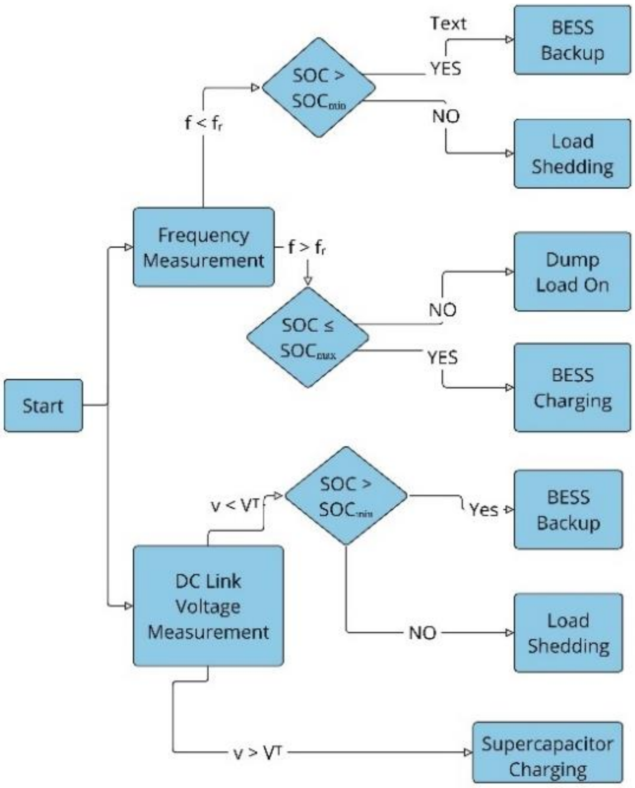

Figure 23 Flow diagram for control strategy in. *Source:* Asghar et al., (2017).

Nonlinear controllers such as model predictive control (MPC) and SMC greatly benefit from AI-based techniques to address changing operational conditions, unknown uncertainties and dependency on the plant model. In (Yang & Wai, 2021), a model-free self-constructing fuzzy neural network (SCFNN) was developed to imitate the SMC for tracking the parallel inverter currents in a grid-connected AC MG.

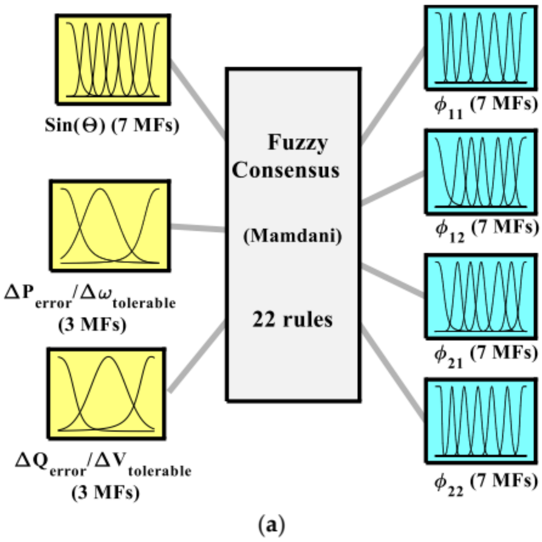

Figure 24 Fuzzy system for consensus control. *Source:* Eskandari et al., (2018).

5.3. Machine learning (ML)

ML uses data-driven algorithms, such as artificial neural networks (ANNs), to analyze data, identify patterns, and make predictions with high accuracy. For inverter-interfaced MGs, ANNs are categorized as supervised learning, unsupervised learning, or reinforcement learning (RL). A notable subfield, deep reinforcement learning (DRL), combines ANN RL. DRL trains agents to learn progressively through trial-and-error by interacting with the environment, offering a robust framework for dynamic decision-making.

Supervised learning aims to establish implicit mappings and functional relationships between inputs and outputs via a training dataset consisting of input–output pairs. This capability is particularly valuable in applications where system models are often complex and difficult to define. Unlike supervised learning, which relies on input–output pairs in the dataset, unsupervised learning does not involve output data for the learning target during the training process. It learns patterns from unlabeled datasets. Reinforcement learning (RL) does not rely on a preexisting training dataset. Instead, its objective is to determine an optimal action strategy that maximizes rewards for a specific task. This process is essentially a dynamic programming or optimization problem. RL achieves this goal-oriented strategy through interactions with systems or simulation models, using a trial-and-error approach to refine its decisions progressively.

To address the challenges of power sharing in droop control and to regulate frequency in an islanded MG, a novel intelligent approach based on an ANN was introduced in (Vigneysh & Kumarappan, 2016). This approach employs an FFNN trained via the Levenberg–Marquardt (LM) algorithm. Training data are obtained from a simplified MG system featuring a single DG unit operating under different load scenarios. The trained FFNN addresses the limitations of traditional droop control by ensuring accurate sharing of real and reactive power among DG units while accounting for the complexity of line impedance. Furthermore, it provides effective control of the MG voltage and frequency across all operating conditions.

In (Zheng et al., 2022), a data-driven online algorithm based on an ANN was proposed to replace the conventional hierarchical droop control framework. The proposed algorithm employs NNs to develop a data-driven nonlinear control law in real time without requiring an accurate system model or precise system parameters. The control law is dynamically updated during operation, eliminating the need for a prior training phase. This makes the algorithm particularly well suited for plug-and-play scenarios. This approach enables faster convergence of frequency and active/reactive power-sharing errors, with the added advantage of allowing online weight updates. This feature enhances the system's robustness to changes in the physical plant.

Reference (Issa et al., 2022) proposes a model-free approach for developing VSM control for GFM inverter-based DGs in the ACMG. A supervised ANN controller is trained with a dataset collected from a VSG control for more than 70 different scenarios, which greatly increases the robustness and stability during extreme load variations.

Reference (Norouzi et al., 2024) addresses limitations in traditional model-based control methods for virtual inertia (VI), which rely heavily on specific operating conditions and lack robustness. It introduces a novel behavior simulation logic (BEL) approach to emulate the VI and damping for effective system frequency control. This model-free controller eliminates the need for prior knowledge of system parameters or configurations, ensuring adaptability to varying conditions, nonlinearity, and uncertainties in MGs.

An ML ANN algorithm for adjusting VSM coefficients under various operating conditions in power systems is proposed. Additionally, DRL algorithms, such as the deep deterministic policy gradient (DDPG) (Skiparev et al., 2023) and twin delayed DDPG (TD3) (Oboreh-Snapps et al., 2024) algorithms, have been applied to VSM control in the ACMG. A comparative evaluation of these two DRL algorithms was conducted in (Benhmidouch et al., 2024) to develop an adaptive VSM control strategy for GFM inverters, aiming to enhance frequency dynamics.

6. Future Trends

As IIDG units play an increasingly dominant role in MGs, further research is essential to enhance power sharing, stability inverstigation and voltage and frequency. Several key future trends will shape the next generation of high-performance inverter-based MGs, addressing stability challenges, adaptive control mechanisms, and intelligent optimization techniques.

6.1. Stability and robust control for dynamic loads

One of the primary challenges in IIDG-based MGs is maintaining stability under variable load conditions, particularly during transitions between grid-connected and islanded modes. Current droop control methods struggle with nonlinear load behavior, leading to inaccurate power shaping and adding to frequency and voltage fluctuations. Future research will focus on enhancing robust control frameworks, such as adaptive droop control, virtual impedance methods, and impedance shaping, to improve the overall stability of MGs.

6.2. Sensitivity issues in nonlinear droop control

Traditional droop control strategies often assume linear system behavior, but in practical applications, nonlinear interactions between IIDGs and networked loads impact system performance. Addressing sensitivity issues in nonlinear droop control requires advanced modeling techniques and data-driven learning approaches to dynamically adjust droop gains, ensuring reliable power sharing and system stability.

6.3. Cost-optimized droop control with adaptive gains

Future research on droop control optimization will explore cost-aware strategies, where droop gains are dynamically adjusted on the basis of real-time system conditions and operational cost functions. This requires the integration of machine learning (ML) algorithms with real-time optimization techniques to balance power-sharing accuracy, cost efficiency, and system stability. Hybrid AI-based controllers are likely deployed to fine-tune droop parameters for enhanced economic operation.

6.4. Accurate power sharing in grid-connected and islanded modes

Transitioning between islanded and grid-connected operations introduces challenges in terms of power-sharing accuracy. Traditional controllers often fail to adapt quickly to changing conditions, leading to power imbalances and transient instability. Future solutions will involve hybrid control methods, combining nonlinear control techniques and intelligent AI-based controllers to predict, adapt, and optimize real-time power distributions between IIDGs.

6.5. Networked MGs and advanced topologies

The increasing prevalence of networked MGs—where multiple inverter-based MG clusters interact— demands enhanced distributed control strategies. Droop control must be adapted for multilayer MG coordination, ensuring stable power sharing while avoiding circulating currents and resonance issues. Future research will focus on multiagent control architectures, reinforcement learning (RL)-based controllers, and predictive models for networked MG stability enhancement.

6.6. Impedance shaping for adaptive grid stability

The implementation of impedance shaping has proven effective in stabilizing IIDG-based MGs, but current virtual inductance methods exhibit performance limitations. Future research will explore adaptive impedance shaping, allowing MGs to dynamically adjust the impedance of grid-forming inverters on the basis of real-time grid conditions. This approach enhances system flexibility, especially during plug-and-play DER integration, load variations, and islanded-to-grid transitions.

6.7. Advanced battery energy storage system (BESS) integration

The BESS plays a vital role in stabilizing the MG voltage and frequency, but further research is needed to optimize its economic operation and dynamic performance. Future trends include multitimescale BESS control strategies, integrating real-time optimization, adaptive droop mechanisms, and predictive ML models to improve energy efficiency, reduce storage degradation, and enhance grid stability.

The future of high-performance inverter-based MGs will be shaped by advances in robust control, AI-driven optimization, networked architectures, and fault-tolerant designs. Research will continue to refine control algorithms, improve stability in dynamic operating conditions, and enable intelligent, self-adaptive MG systems. As renewable penetration increases, the development of autonomous, data-driven control solutions will be crucial in ensuring scalability, resilience, and cost-effective operation of next-generation MGs.

7. Conclusion

The development of primary control strategies for ACMGs plays a critical role in ensuring stability, efficient power sharing, and seamless operation across different operating conditions. Traditional droop-based methods have long been used because of their simplicity and lack of communication dependency; however, they suffer from power-sharing inaccuracies, frequency deviations, and voltage regulation challenges, particularly in low-inertia and high-penetration renewable energy systems. Advanced strategies, such as virtual synchronous machine (VSM) control, adaptive droop control, and robust nonlinear techniques (e.g., H∞ control, sliding mode control, and backstepping), have been introduced to address these limitations.

The study highlights that integrating artificial intelligence (AI) and machine learning-based controllers can further enhance adaptability, allowing real-time optimization of MG control. The shift toward intelligent, self-learning systems represents a crucial step forward in improving resilience, efficiency, and reliability in modern power networks.

Despite these advancements, the complexity of MG dynamics—arising from the variability of RES, distributed energy resources (DERs), and evolving load demands—necessitates continuous improvements in control methodologies. The trade-offs between complexity, cost, and computational requirements remain key challenges in deploying scalable and robust primary control solutions.

Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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