HYDROGEN, FUEL CELL & ENERGY STORAGE

A brief review on the application of the virtual impedance method in islanded alternating current microgrids to control reactive power sharing

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Abstract

To preserve power quality in islanded alternating current (AC) microgrids (MGs), precise line voltage regulation is crucial, especially in the presence of non-linear and unbalanced loads. Effective coordination among multiple distributed generation units is essential to meet the load requirements and maintain system stability. Disparities in line impedance often lead to unequal power distribution among distributed generation units in microgrids. This paper provides an overview of virtual impedance (VI) techniques and droop control. Typically, these techniques are combined to achieve equitable power distribution among dispersed generation units in microgrids with lines of varying impedances. In a stable state, the frequency of the distributed generation units within the microgrid remains uniform, facilitating accurate active power sharing. However, the voltage measurements from distributed generation units are often non-uniform, making reactive power sharing challenging in the microgrid. To address this issue, virtual impedance (VI) can be introduced by placing an additional impedance virtually between the inverter and the load in the physical circuit. This adjustment allows for modification of the inverter's control strategy. By integrating VI with droop control, the impedance observed at the converter's output is adjusted to counteract the coupling effects between active and reactive power, thus improving reactive power sharing and overall system performance in the microgrid.

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1 Introduction

Energy is a fundamental element for most activities, and its supply is influenced by various factors. With the expansion of industrial centers and the increase in consumption loads, there is a growing demand for reliable, high-quality, and affordable energy. Consequently, there is a need to increase energy production to meet these demands [1, 2]. Renewable energies crucial for addressing environmental and economic concerns by mitigating the adverse effects of fossil fuel consumption and promoting sustainable energy solutions [3, 4]. However, to transfer energy from remote areas to consumption centers, extensive energy transmission networks are needed. These networks often face challenges such as energy losses and reduced security margins for maintaining network stability [5, 6]. The presence of distribution networks can lead to frequent interruptions and instability [7,8]. In recent years, economic, technical, and environmental factors have driven the expansion of microgrids (MGs) connected with renewable energy sources (RESs) [9, 10]. The integration of energy sources such as solar photovoltaics [11, 12], wind turbines [13,14], and power storage elements [15,16] has facilitated the production of decentralized energy [17,18]. The integration of renewable energies and the use of distributed generation (DG) units have reduced the need to expand networks to supply power to remote loads [19, 20]. However, the incorporation of DG into the power system impacts several technical features of the network, such as the system's equivalent inertia and the distribution of power among DG units [21,22]. Considering the intermittent and random characteristics of RESs, power generation from distributed production sources is subject to constant fluctuations [23,24]. The differing voltage levels among each distributed generation (DG) unit complicate the configuration of reactive power sharing. However, since all DG units typically operate at the same frequency, active power sharing remains relatively straightforward [25, 26].

If the capacity of DG energy resources is lower than the load demand, the system frequency will decrease [27]. DG energy sources provide customers with clean and reliable electricity while reducing transmission and distribution losses. By utilizing local energy sources, DG also minimizes energy loss in the power delivery system [28,29]. To maximize the benefits of integrating distributed renewable resources into the power system, it is crucial to optimize both the size and location of these generation units. Improper placement of distributed renewable generation units can lead to increased system losses, voltage drops, higher harmonic production, and reduced voltage stability [30, 31]. The incorporation of distributed production units into the electrical energy system presents several challenges, including issues related to the sensitivity of protection systems, maintaining required voltage levels, and managing fluctuations in emergency currents [32,33]. Operational stability and control are critical due to factors such as frequency, voltage regulation, optimal power transfer, and islanding detection in both microgrid operational modes [34, 35].

Dividing the reactive power produced by DG components in a MG is challenging due to factors such as transmission line impedance and other considerations [36,37]. As the electricity industry expands and microgrids are increasingly used to mitigate problems, the role of control systems has also become crucial [38, 39]. VI is a control method used in conjunction with droop control to regulate power and energy distribution in microgrids. The droop control method allows for the coordination of distributed generation facilities without requiring direct communication between parallel inverters [40, 41]. Given the increasing importance of microgrids, several review studies have explored various aspects of their implementation and management [42,43]. One of the critical areas of focus for researchers concerning microgrids (MGs) includes energy management, control, stability, and protection [44,45]. Table 1 provides a summary of various review studies addressing these topics.

The Virtual Impedance (VI) method has been applied in various studies to enhance the performance of microgrids (MGs) [46, 47]. Notable applications of VI in MGs include: Designing harmonic VI to optimally manage power quality [48], enhancing the power inverter output current regulator in unbalanced situations using VI [49], limiting fault current in inverter-based distributed generation (DG) systems with VI [50], and implementing VI control for an energy-sharing approach [51]. One operational condition of microgrids (MGs) is island mode, which occurs when the MG disconnects from the main network due to an error [52,53]. This article provides a brief overview of the Virtual Impedance (VI) method in islanded alternating current (AC) MGs for reactive power distribution. The objectives of the review are as follows:

- Investigating the performance of alternating current MGs in different operational modes
- Classifying MGs based on various parameters
- Investigating control methods related to loss and VI in AC MGs.
- Presentation of existing simulation results on control methods for loss and VI in AC MGs.

The arrangement of the article is as follows: In section 2, two functional modes of the MG, including islanded and connected to the network, are described.

The droop control approach does not require communication connections among the parallel power inverters to coordinate between the DG facilities in the MG. In section 3, the droop control approach is discussed, including its advantages and disadvantages. Section 4 illustrates the use of virtual impedance (VI) in islanded MG operation. It details how frequency droop, amplitude droop, VI droop, and adaptive VI are controlled by inverters to achieve proportional load sharing between parallel inverters, and section 5 provides the conclusion of the study.

Table 1. A number of review studies in different fields of microgrids.

Subject	Ref.	Research Prominence
Control	[54]	To meet load demands, coordination among multiple distributed generation (DG) facilities is essential. Various control schemes have been developed to manage load distribution in DG networks using parallel inverters. In order to coordinate among the DG units in the MG, the droop control approach does not require a communication interface between parallel power inverters. Several droop control strategies have been explored to facilitate coordination among DG units in the MG. Common issues associated with droop control include reliance on line impedance, delayed transient response, and improper power sharing.
	[55]	Remote locations can reliably receive energy through direct current (DC) microgrids, but this requires a robust control system. Hierarchical control mechanisms have been investigated and proposed to provide reliable and efficient regulation for DC microgrids. In a hierarchical control system for direct current (DC) microgrids, the control levels are structured as follows: 1. First Level: Manages current and voltage adjustment. 2. Second Level: Addresses current and voltage error correction. 3. Third Level: Regulates energy and power to minimize power losses.
Energy Management	[56]	Energy management in MGs is an information and control system designed to optimize performance in both production and distribution systems. It aims to ensure energy supply while minimizing costs. A review of energy management in MG systems using renewable energy has been conducted. This review includes a comparative analysis of optimization objectives, constraints, and simulation tools applied to MGs in both operational modes.
	[57]	The rapid reduction of fossil fuels and the need to protect the environment have heightened the importance of integrating renewable energy sources (RESs) into the energy system to meet energy demand. Investigations have focused on the architecture, control structure, and energy management system of direct current (DC) microgrids. Different methods and strategies of energy management of direct current MGs are presented, focusing on size and cost optimization. The review includes multiple optimization techniques used to enhance the efficiency and economic feasibility of DC microgrid systems.
Stability	[58]	The connection of scattered energy sources in the MG is typically established through inverters interfacing with the city grid. As a result, the stability characteristics of the MG differ from those of a traditional grid. A stability categorization technique for microgrids (MGs) is proposed based on the MG's characteristics, including its type of operation, the types of disturbances it encounters, and the duration of those disturbances.
	[59]	Given the rapid development of microgrids (MGs), it is essential to analyze their large-signal stability. This analysis helps understand system dynamics during disruptions and assesses the MG's ability to successfully rejoin the main grid. Analytical analysis of large-signal stability approaches for inverter-based AC microgrids (MGs) has been conducted. This includes energy function analysis and Lyapunov-based methods for assessing large-signal stability.
Protection	[60]	To ensure reliable and secure operation of MGs, sophisticated protection mechanisms must be designed and selected. The integration of various technologies within MGs increases the likelihood of errors and complicates protection actions. Different protection techniques have been studied to ensure that microgrids (MGs) operate correctly across various topologies and connections. These techniques address the unique challenges posed by different configurations and integration scenarios.
	[61]	Microgrids (MGs) operate in two modes: grid-connected and islanded. While MGs offer significant benefits to the energy system, their integration into distribution grids has introduced challenges for the protection system. Various protection concerns in microgrids (MGs), such as fault currents under different operating conditions and bi-directional fault currents, have been investigated. Potential solutions for addressing these faults have also been explored.
Optimization	[62]	To enhance microgrid (MG) operation, it's important to address the intermittent nature of renewable energy sources (RESs) and issues related to low power quality. Heuristic optimization mechanisms have been employed to tackle these challenges. An overview of meta-heuristic optimization algorithms and their role in improving the operational performance of MGs is provided. Various issues related to microgrids (MGs), including techno-economic analysis, control, load forecasting, fault detection, flexibility improvement, and energy management, have been investigated. The research indicates that the Gray Wolf Optimization method, Genetic Algorithm, and Particle Swarm Optimization were respectively employed for optimizing MG performance.
	[63]	Meta-heuristic optimization techniques have been employed for MG optimization. Selecting the most effective optimization technique is crucial for minimizing MG costs. Investigations have been conducted on six meta-heuristic techniques, including Differential Assessment and Whale Optimization. A comparative study using performance indicators has been provided to evaluate their effectiveness.

2 Functional modes of microgrid

Typically, a MG consists of a local power generation infrastructure, an energy storage system (EES), various loads, and a grid connection point. MGs facilitate local energy trading between consumers and contribute to the growth of a decentralized energy market [64,65]. MGs typically include DG units, RESs and EESs as some key components. The complexity and behavior of MGs are influenced by the number of distributed loads and energy sources they incorporate. MGs offer a stable power supply, support the main grid during peak demand periods, and help prevent blackouts and grid instability by balancing supply and demand.

Figure 1 illustrates the categorization of microgrids (MGs) based on various parameters, including control strategy, distribution system, and MG components. According to their electrical characteristics, MGs are classified into three categories: direct current (DC) MGs, alternating current (AC) MGs, and hybrid MGs.

A general structure of an alternating current MG is shown in Figure 2. Typically, MGs operate in two modes: grid-connected mode and islanded (or independent) mode [66,67]. There are differences between these two modes both in terms of advantages and challenges. In grid-connected mode, the primary role of the controller is energy management. In contrast, during islanded operation, the controller is tasked with additional responsibilities, including voltage and frequency management, as well as energy management and load power sharing [68, 69]. When connected to the main grid, the microgrid imports power from and exports power to the central grid. In other words, when the microgrid is connected to the central power system, it shares power with the grid. It is allowed to supply reactive power and participate in energy demand planning with the main grid.

However, when operating in island mode, the microgrid is not electrically connected to the main grid, and therefore, the main grid has no impact on its performance. In this case, the DG units connected via the voltage source converter are responsible for controlling both voltage and frequency. To prevent overload in an islanded MG, the DG units must share the power among themselves, ensuring that both frequency and voltage remain within permissible limits. When operating in island mode, MGs face significant challenges such as power sharing issues and circulating currents. Variations in line impedance among inverters connected to the electrical network affect the accuracy of power sharing [70, 71]. In such scenarios, the conventional droop control technique is insufficient for effectively distributing the system's reactive power [72].

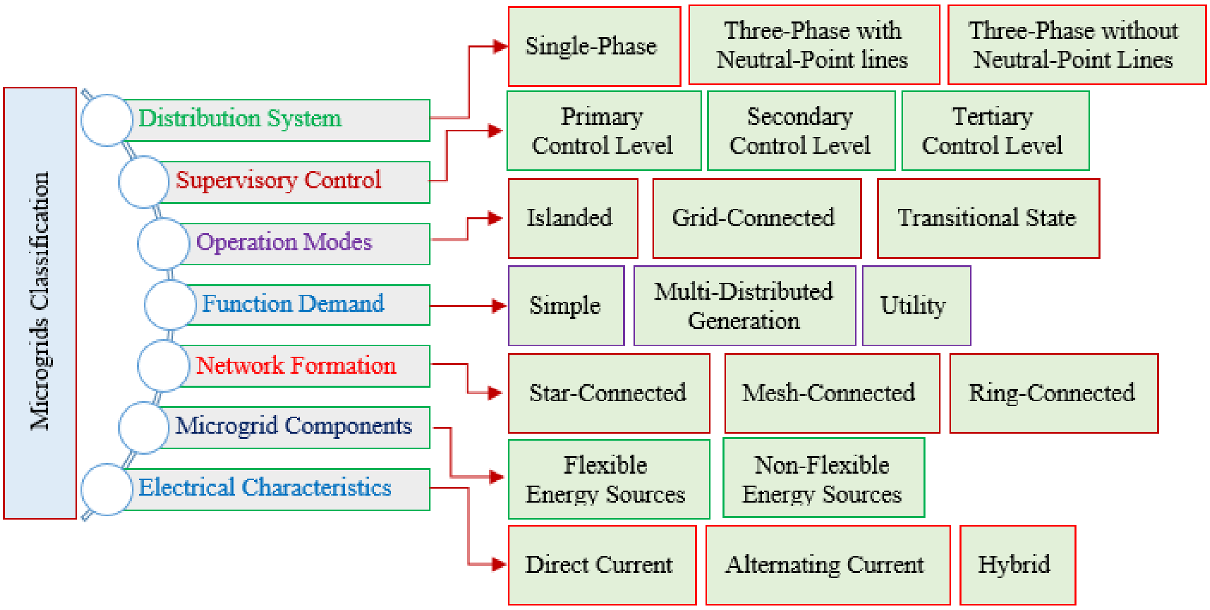


Fig. 1. Classification of microgrids.

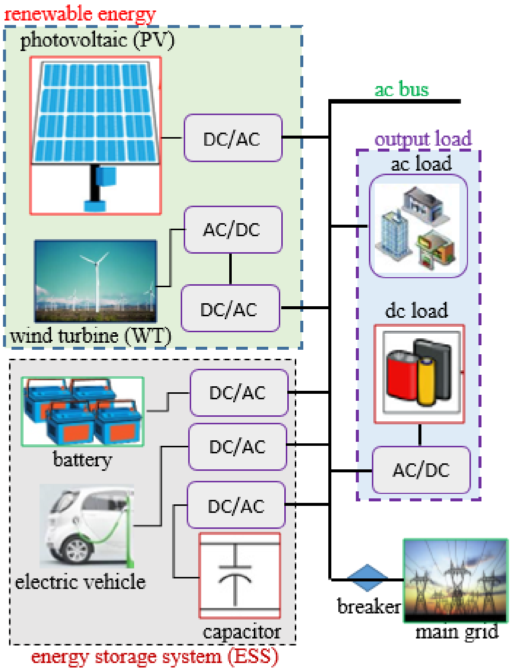


Fig. 2. Typical structure of an alternating current microgrid.

3 Droop control method

Coordination among different distributed generation (DG) units is essential to meet load demand. Various control strategies have been proposed for managing load supply through parallel power inverters in DG networks [73, 74]. Power control methods in inverters include V/f control, PQ control, and loss control [75]. For AC MGs, droop control is typically based on voltage, active power-frequency and reactive power characteristics. In contrast, for direct current MGs, droop regulation generally relies on voltage-current characteristic or active voltage-power relationships [76]. Control techniques using droop, reactive power-voltage (Q-V) and active power-frequency (P-f) are effectively employed in MGs to manage the contribution of reactive and active powers [77]. The simplicity and lack of need for communication between active generators have made these methods widely used in MGs [78]. Figure 3 illustrates the relationships between active power and frequency, as well as between reactive power and voltage. The droop characteristics can be represented as follows:

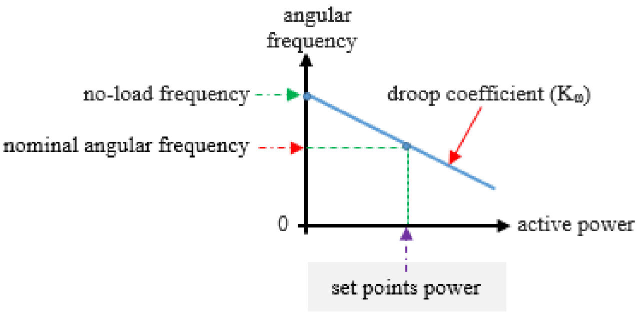
$$\omega = \omega_n - K_\omega P\,, \tag{1}$$

$$V = V_n - K_V Q\,, \tag{2}$$

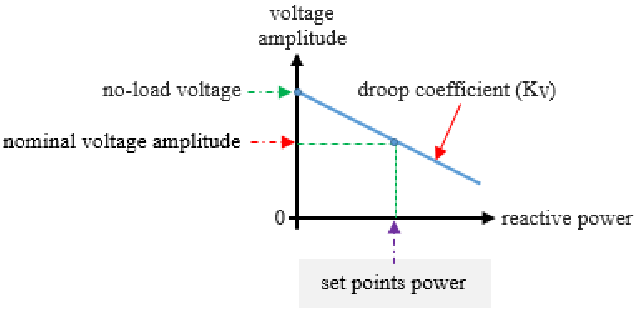
where ω denotes the angular frequency, with its nominal value being ω_n. V represents the voltage magnitude, with its nominal level being V_n. The slopes for reactive power and active power are K_V and K_ω, respectively.

To ensure optimal power distribution between inverters during island mode operation and precise management of the power injected into the grid during grid-connected mode, droop control plays a crucial role in regulating the output power [79]. Despite its operational simplicity and decentralized structure, droop control often results in inadequate reactive power sharing due to mismatches between local load displacements and feeder impedances. Additionally, droop control tends to perform poorly with low power quality when handling nonlinear loads [80, 81]. Also, droop control has poor performance with low power quality when dealing with nonlinear loads [80, 81]. The droop relationship between voltage and reactive power in the conventional droop regulation techniques is nonlinear due to the filter reactance. In short, the disadvantages of the conventional droop control techniques include:

- Effect of system parameters,
- Applicability limited to highly inductive transmission lines,
- Inability to handle non-linear loads,
- Failure to ensure proper voltage regulation,
- Inherent trade-off between accurate power distribution and voltage control,
- Dynamic dependency of power distribution on loss control coefficients and the energy calculation method,



(a) Active-frequency power



(b) Reactive power-voltage

Fig. 3. Droop characteristics

Controller speed adjustment for both active power controller and reactive power controller can affect frequency and voltage controls [82, 83]. To meet the growing power demand, coordination between various DG facilities is necessary [84, 85]. Numerous advancements in droop control methods have emerged, offering various approaches to enhance traditional droop techniques [86, 87]. Among these improved droop methods are VI method [88], adaptive droop control [89,90], angle droop control [91, 92], virtual frame transformation [93,94] and virtual inertia-based droop control [95].

To decouple reactive and active powers, a technique that involves converting the frequency and voltage frame into a virtual frame is presented in [96]. This method necessitates real-time management of the output impedance of each distributed generator within the MG, along with other grid characteristics. However, the implementation of this type of regulator is feasible only for small networks with constant load and network components, making it impractical for large-scale MGs.

The power generation in MGs primarily comes from renewable sources, which are inherently variable. Traditional controllers often struggle with the wide range of operational scenarios due to the regular fluctuations and uncertainties in power systems. In [97], frequency management in AC MGs was examined using particle swarm optimization (PSO) and fuzzy logic techniques.

As illustrated in Figure 4, the dynamic response of the MG system is demonstrated using a load disturbance pattern, or multi-stage load. Figure 5 shows the frequency deviation for three different controllers. It is evident that the fuzzy PI controller designed using the PSO technique outperforms the standalone method in terms of settling time and control effort for minimizing frequency deviation.

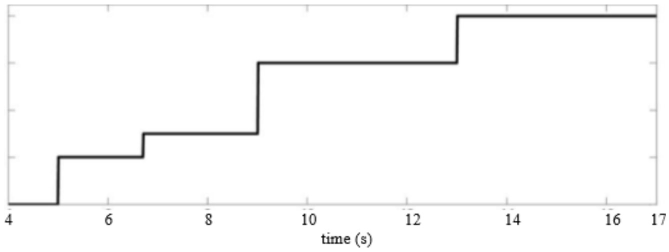


Fig. 4. Load disorder pattern.

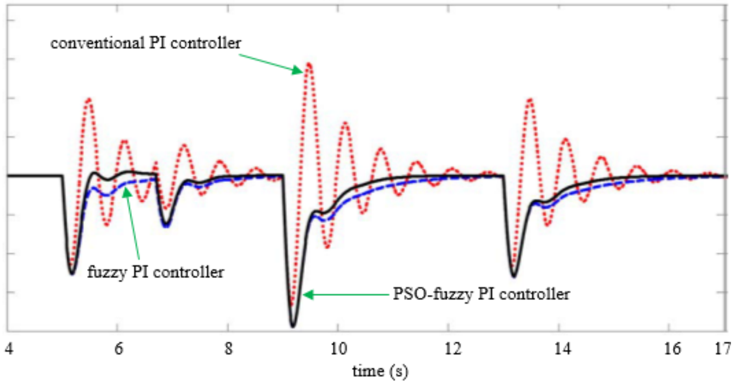


Fig. 5. Comparison of microgrid frequency deviation response for three different control algorithms.

4 Virtual impedance method

Resistance and inductance together constitute the VI. By introducing an extra impedance between the power inverter and the load in the physical circuit, VI enables modifications to the control of the power inverter. This approach allows the controller to adjust the effective impedance between the inverter and the load. VI functions similarly to a conventional impedance while simultaneously minimizing losses [98,99]. This method addresses impedance mismatches to prevent circulating currents and unbalanced power sharing. VI is utilized to analyze microgrid (MG) impedance by incorporating a feedback control loop into both the voltage and current control loops within the MG [100, 101].

The VI is configured to adjust the output impedance of the converter based on the resistance-to-reactance ratio. With the VI applied in the control loop, the characteristics of distributed generation (DG) units are no longer solely determined by loss equations. Each DG unit's regulation method includes an output current feedback loop, as illustrated in Figure 6, which incorporates the VI [102].

Internal control manages the current and voltage levels at the inverters' output. In island mode operation for the microgrid (MG), the inverters are solely responsible for controlling the voltage level. In other words, voltage control is the primary objective of the internal control loops. The objective of controlling both the current and voltage loops is to adjust the output voltage of the power inverter to align closely with the desired voltage of the microgrid (MG) [103].

In the VI technique, determining the appropriate VI value is a key challenge. A higher impedance value enhances power separation but can lead to increased voltage droop, potentially causing network instability. To address this, either a fixed or adaptive VI can be used. Given that grid conditions, such as loads and renewable generation levels, are constantly changing, an adaptive VI approach is generally more effective [104, 105]. Figure 7 illustrates the block diagram of adaptive VI control. The amount of reactive power demand of each inverter is calculated from the following equation [106]:

$$Q_{\text{demand}} = \frac{Q_{\text{total}}}{\sum_{k=1}^{n} Q_{\text{rated},k}} Q_{\text{rated}} \,, \tag{3}$$

where $Q_1, Q_2, \ldots, Q_n$ controller determines the reactive power contribution of each inverter based on the total rated reactive power. To adjust the Virtual Impedance (VI) of the distributed sources, the controller calculates the difference between the measured reactive power demand and the actual reactive power output.

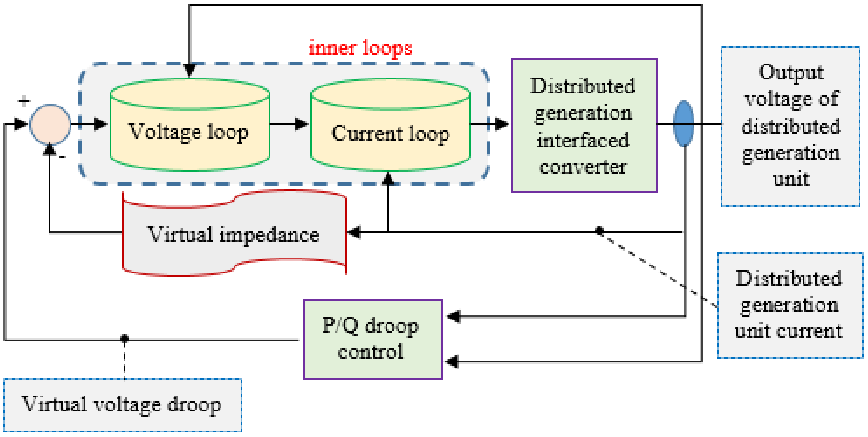


Fig. 6. Control diagram in direct current microgrids using virtual impedance.

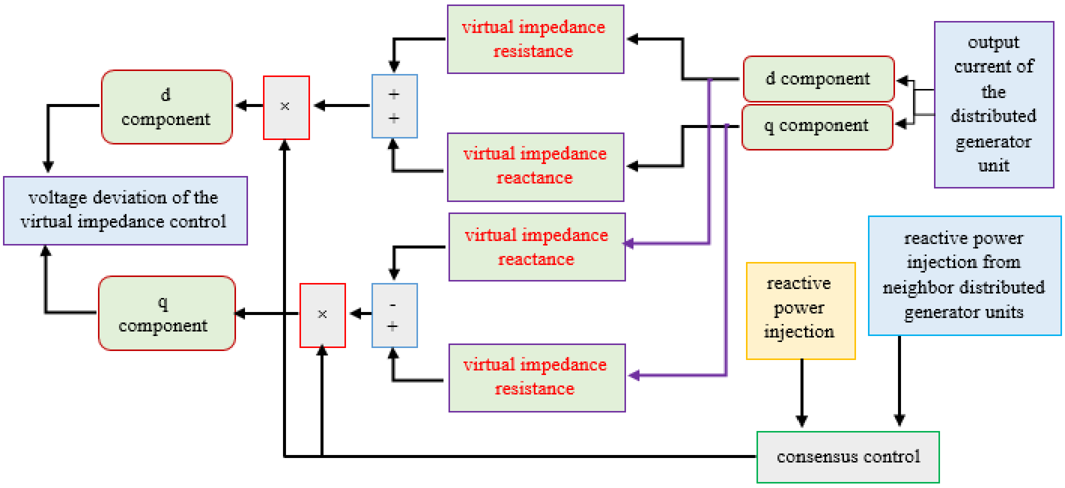


Fig. 7. Block diagram of adaptive virtual impedance control.

Various techniques for adaptive VI control have been proposed, including [107,108]: Decentralized control [109], Low-bandwidth communications [110], Distributed secondary control [111], virtual synchronous generator control [112], and voltage source converter output impedance adjustment [113] can be mentioned.

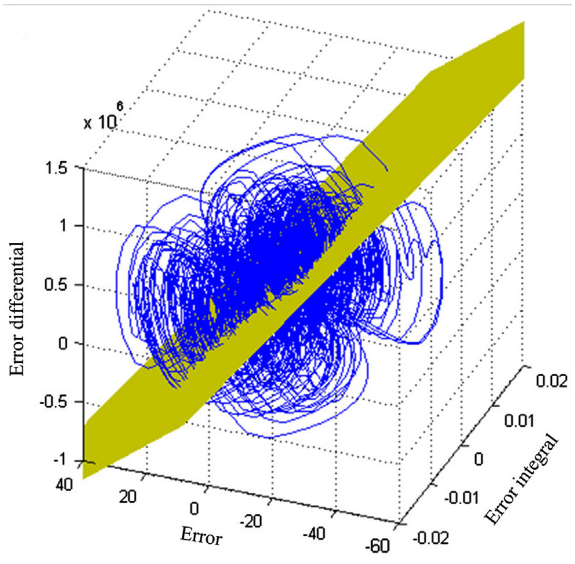
A distributed current control technique for parallel power inverters is presented in [114]. In this method, the virtual resistance is adjusted based on the fault size and the reactance corresponding to the phase angle of the fault. This adjustment ensures a consistent output current from the inverter. The technique then modifies the equivalent impedance of the inverter across positive sequence frequencies, negative sequence frequencies, and harmonic frequencies. Line impedance is a significant issue affecting power mis-sharing among distributed generation (DG) units. The droop control strategy, commonly used in microgrids (MGs) to manage parallel inverters, often encounters challenges with uneven reactive power sharing due to line impedance mismatches. To address these issues, a loss control strategy based on adaptive voltage and current (VI) is proposed in [115]. This strategy does not rely on communication and aims to resolve reactive power sharing problems caused by line impedance differences. The input signals for the impedance matching controller include the output reactive power and the voltage of each distributed generator. Utilizing droop control for decentralized power sharing in medium-sized generators (MGs) has proven effective However, the primarily resistive nature of low-voltage networks and the varying line impedances among converters present challenges for equitable reactive power sharing.

The significance of the transient VI component is discussed in [116]. A small-signal state-space model is presented to illustrate the impact of including the transient VI. Simulation results and eigenvalue analysis indicate an improvement in damping with the addition of the transient VI. In [117], distributed secondary control techniques are discussed to minimize reactive power errors in the presence of improper feed lines. The study details the mathematical modeling of adaptive VI control for sharing both reactive and active power among distributed generators (DGs). Hierarchical control, which includes both primary and secondary control levels, is also examined. Simulation data suggests that leader-follower consensus control performs well for small systems, while leaderless consensus control is a more reliable option for larger distributed generation systems. The control system for parallel inverters in islanded microgrids (MGs) is explored in [118], where an adaptive sliding mode controller is employed to enhance disturbance rejection performance within the regulation system.

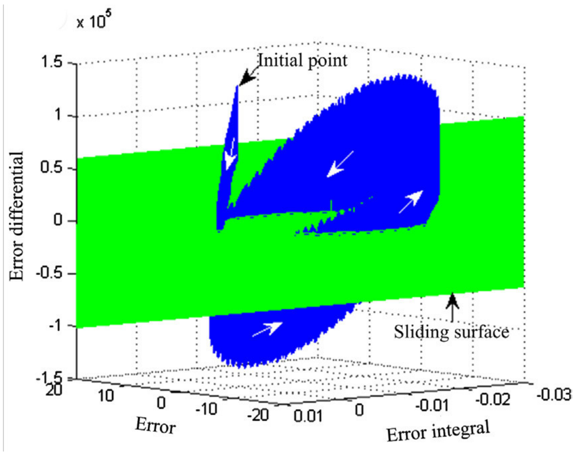
Additionally, adaptive algorithms are utilized to ensure the robustness of the inverter control system by monitoring both external and internal disturbances. Three types of PID controllers – conventional sliding mode controller and adaptive sliding mode controller – are compared for the inverter control system. The state trajectories in the phase space are illustrated in Figure 8. Ideally, the control function should cause the state path to move from the initial point swiftly towards the sliding surface and, after sliding along this surface, ultimately converge to the origin. Inverter system performance can be monitored using one of four techniques: robust control, nonlinear control, artificial intelligence control algorithms, or disturbance observer-based control. Reference [119] explores the susceptibility of voltage source inverters to load variations and parameter perturbations. An enhanced nonlinear extended state observer (NLESO) is combined with a rapid terminal sliding mode control technique. Simulation results indicate that the NLESO improves disturbance rejection capability, maintains the first derivative peak, ensures high tracking accuracy, and achieves low total harmonic distortion. The state paths are illustrated in Figure 9, and the rate of change is depicted in Figure 10. The VI is an open-loop control that may potentially overload the DG unit. To address this, a closed-loop control scheme is proposed in [120] to manage harmonic and unbalanced power distribution among DG units. This approach uses the lowest DG output impedances to optimize power quality, with absorbed power and residual capacity considered as feedback signals.

5 Conclusion

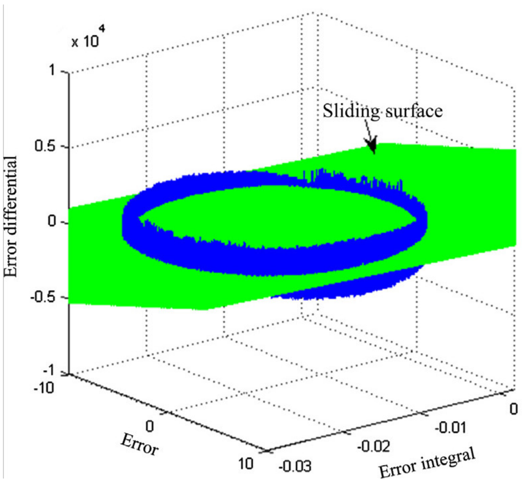
Energy production and consumption impact on social, economic and environmental issues. MGs can operate either connected to the main grid or independently from it. In large island networks, impedance mismatches can reduce the performance of power sharing. This article provides a brief overview of the application of the VI technique in droop control methods for managing power sharing. In island mode, all load power demand must be distributed among multiple distributed generation (DG) units. Droop control based on the Voltage-Current (VI) technique is a method used to enhance the robustness of power sharing among DG units in a microgrid (MG) operating in island mode. VI improves performance under nonlinear load conditions, helps dampen fluctuations, and increases system stability.



(a) PID controller



(b) normal sliding mode controller



(c) adaptive sliding mode controller

Fig. 8. Status paths of the inverter control system for three types of controllers in the phase space.

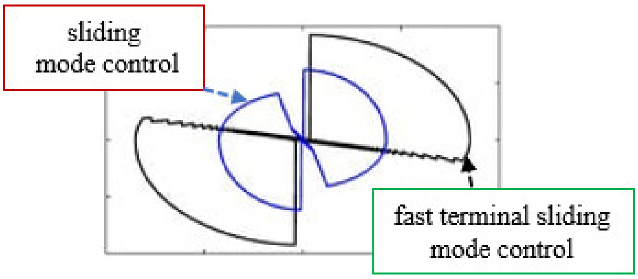


Fig. 9. State paths in the phase plane for sliding mode control and fast terminal sliding mode control methods.

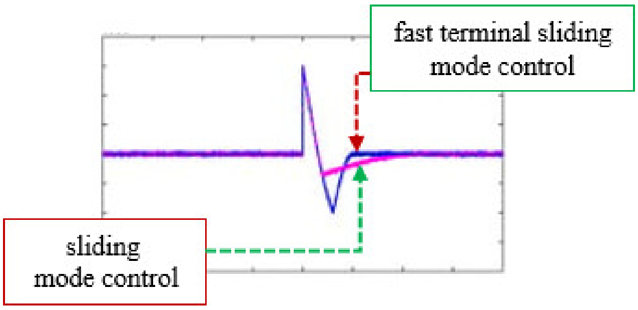


Fig. 10. Output voltage error change rate for sliding mode control and fast terminal sliding mode control methods.

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