Analysis of Optimization Strategies for Inverter Circuits in Microgrid Independent Power Generation

Sizhuang Zhou*

Detroit Green Technology Institute, Hubei University of Technology, Wuhan, 430040, China

*Corresponding author: 2211621114@hbut.edu.cn

Abstract. With the continuous growth of global energy demand and the increasingly severe environmental problems, microgrid technology, as an important direction of energy transition, has been developing rapidly in China's construction in recent years. This paper systematically introduces the basic concept, structure, power source and its power supply mode of microgrid, and deeply analyzes the optimization strategy of inverter circuits in independent power generation of microgrid. The performance of inverter circuit, as a key technology for converting DC power to AC power in microgrid, directly affects the energy conversion efficiency and power supply quality of the grid. This paper focuses on the improved sag control strategy and virtual synchronous generator (VSG) strategy, which significantly improve the stability and power quality of microgrids by enhancing the flexibility of power control and the adaptability to renewable energy sources. By comprehensively analyzing the current literature and research results, this paper reveals the central role of sag control in independent power generation in microgrids and points out the reasons why it is indispensable in many studies.

Keywords: Microgrid; independent power generation; sag control; virtual synchronous generator.

1. Introduction

Nowadays, the global energy demand is growing and various environmental problems are becoming more and more serious, the utilization of new energy sources and the development of microgrid technology have become an important direction of energy transition in today's world. Among them, the optimization strategy of inverter circuits in microgrids is one of the key technologies to realize their efficient and stable operation, and the research on this aspect is still very limited.

Inverter circuits can convert direct current (DC) to alternating current (AC) to satisfy different demands for electricity, and their performance directly affects the energy conversion efficiency and power supply quality of the grid [1]. Microgrids, as a kind of self-sufficient small-scale power system, utilize power electronics technology to group and connect power generating devices to the grid, which is even more necessary to ensure this aspect. At present, existing studies include but are not limited to: the design of virtual synchronous generators to achieve the dual advantages of synchronous generators and ordinary inverter power supply [2]. Through the derivation of the principle of generating SPWM waves by the unregulated rule sampling method, the software design based on the TMS320LF2812 chip is given, and the three-phase grid-connected inverter designed by this method [3].

This paper first systematically introduces the structure of the microgrid system and its related power generation principle, and analyzes the reasons as well as the necessity of optimizing the control strategy of the microgrid inverter circuit. Subsequently, the limitations of the sag control strategy are discussed in detail and improvement strategies are proposed, including sag curve intercept compensation and sag curve coefficient adjustment, which help to solve the problem of unbalanced voltage and power distribution [4]. In addition, this paper explores the application of VSG technology, including the provision of virtual inertia and damping, as well as the integration with energy storage systems to reduce frequency deviation and improve system stability, and analyzes the reasons for the dominance of sag control in microgrid control. Finally, the paper looks at the future challenges of microgrid technology, including stability issues at high penetration rates, and coordination and optimization of energy storage systems.

2. Analysis of the principle structure of microgrid system

2.1. Microgrid Concept

A microgrid can be defined as a small power generation and distribution system comprising micro power sources, loads, and monitoring and protection equipment. These are connected to the main grid through a public connection point (PCC) and, depending on the operational mode selected, are capable of functioning either as a self-sufficient entity capable of maintaining regional supply and demand balance or as part of a joint system comprising both the main grid and a distributed power microgrid. The microgrid interacts with the external grid as a unified control unit, thereby enabling it to simultaneously meet customer demands for power quality and security of supply.

Microgrids can be classified into two main categories: DC microgrids and AC microgrids. This distinction is based on the type of internal voltage used. In a DC microgrid, components are directly connected to the DC bus, whereas in an AC microgrid, power electronics link components to the AC bus.

2.2. Microgrid components

An independent microgrid is mainly composed of the following parts: different kinds of distributed power sources or energy storage devices, different kinds of power electronic converters, monitoring and protection equipment, and loads which is shown in Fig.1, while the common modules in power electronic converters are rectifiers, inverters, and converters, etc., and this paper mainly discusses the inverter circuit module.

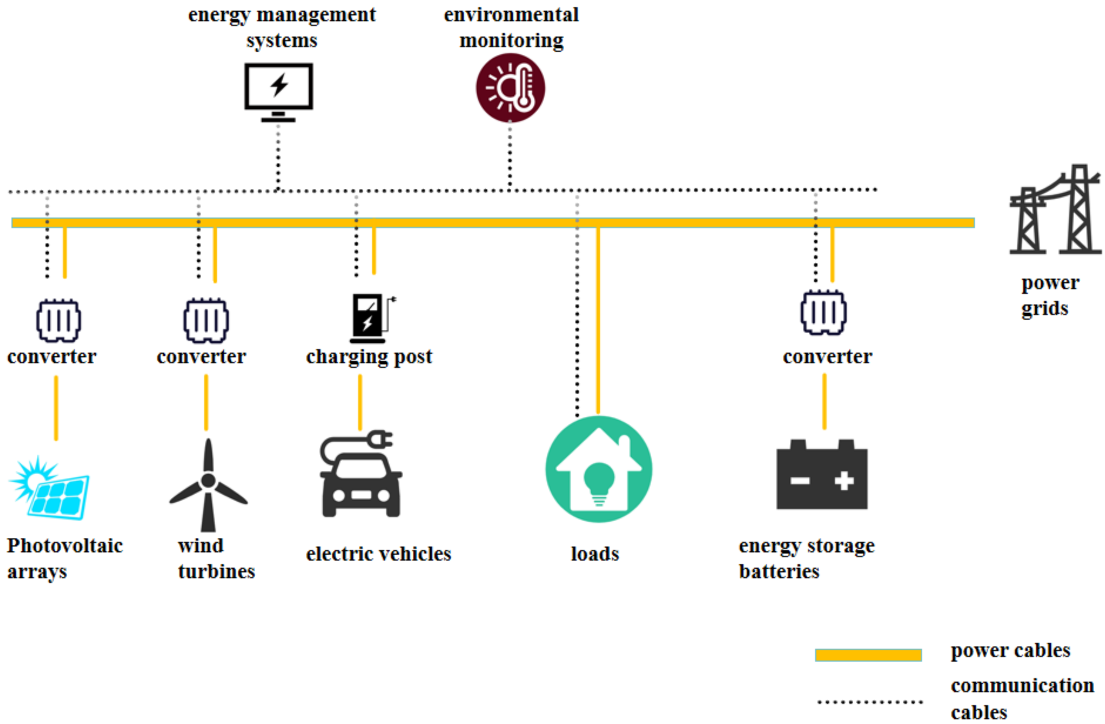

Fig. 1 Smart Microgrid Composition

2.2.1 Microgrid power supply

Most of the power sources for microgrids are distributed energy sources or energy storage systems. Common distributed energy sources include: solar photovoltaic modules, wind power modules, fuel cells, micro-gas turbines, etc. energy storage systems mainly include: battery storage, pumped storage, and supercapacitor storage [5]. Here we mainly introduce photovoltaic, wind turbine and pumped storage systems.

Photovoltaic power generation module: also known as solar cell module, is the core component in the solar power generation system, which converts solar energy into electricity through the photovoltaic effect. When light shines on the semiconductor material, the energy of photons excites electrons to leap from the valence band to the conduction band. Consequently, a potential difference is established between the two extremities of the semiconductor, thereby generating an electric current. The mathematical formula for its daily power generation about the daily emission is:

$$P = I \times A \times \eta \tag{1}$$

Where, P stands for daily power generation (kWh), I stands for daily shot (kWh/m2), η stands for PV panel efficiency, unitless

Wind power module: A wind turbine is a device that employs wind energy to generate electricity. The operational principle of the wind turbine is to utilise wind energy to drive the rotation of the wind wheel, which in turn drives the generator. The wind energy is transformed into mechanical energy and subsequently into electrical energy. Its power generation capacity can be estimated by the following mathematical formula:

$$P = \frac{1}{2} A \cdot V^3 \cdot C_p \tag{2}$$

P denotes the output power of the wind turbine (W), A is the area swept by the wind turbine (m2), V is the wind speed (m/s), C_p is the wind energy conversion efficiency, no unit, usually the maximum theoretical value will not exceed 59.3%.

Pumped storage: harnessing water's gravitational energy to produce electricity, which can efficiently manage renewable energy's variability. It stores energy by pumping water uphill during surplus and releases it to generate power during demand peaks. This method is characterized by high efficiency, large capacity, rapid response, and long-term storage, becoming one of the leading energy storage technologies.

Due to the wide variety of microgrid power supplies, the different standards for generating output power, and the uniformity of the standards required for grid-connection, it is necessary to control these power sources through power conversion. The inverter and inverter circuit of the grid-connected microgrid are the key to realize energy conversion in the whole process. According to the conversion process, the power supply mode can be mainly divided into two categories: DC-AC power supply and AC-DC-AC power supply [6].

2.2.2 Microgrid inverter circuits

The microgrid inverter circuit is a key component in the microgrid system, which converts DC power to AC power for use by loads or for integration into the grid. In AC microgrids, a large number of inverters are included because various distributed power sources and energy storage devices are connected to the AC bus. Whereas DC microgrids omit many DC-AC links and only require inverters when charging energy storage devices, connecting to certain loads, or grid-connected for use. The optimization strategies required for the two types of microgrids are different due to the different locations where the inverters are present.

Key factors to be considered in the design and control of microgrid inverter circuits include system stability, power control flexibility, and adaptability to renewable energy sources. Through reasonable control strategies and system design, the microgrid inverter circuit can effectively support the stable operation of the entire microgrid and the efficient utilization of energy.

2.3. Independent power generation model for microgrids

Microgrid independent power generation is an operation mode for independent microgrids under specific circumstances, i.e., the microgrid is able to operate independently to maintain its internal power supply when the external power grid fails or disconnects.

When the microgrid generates power independently, due to its small size and weak self-regulation ability, the following various problems are the test for the inverter circuit link: power control and sharing, voltage regulation and frequency regulation, islanding detection problem, phase-locked loop synchronization problem, etc. Therefore, several aspects can be improved by optimizing the inverter module.

In this paper, we will analyze various optimization strategies on microgrid inverters starting from finding the existing methods to optimize the above problems, draw a conclusion and look forward to the future challenges.

3. Microgrid inverter circuit technology progress and optimization strategy

Currently, there are two main ideas about the optimization of microgrid inverter circuits as follows: i) Maintaining the stabilization of frequency and voltage when the load varies by sag control, and ii) Designing virtual synchronous generator (VSG).

3.1. Sag control strategy system analysis

Sag control facilitates microgrid synchronization with the main grid and power supply balance by adjusting the voltage or frequency of distributed energy resources (DERs). In DC microgrids, this is commonly accomplished via converter voltage and current modulation. The sag curve is mathematically represented as follows:

$$U_{dcref} = U_o - kI \tag{3}$$

Where U_{dcref} stands for the given output voltage of the unit converter, U_o is the desired value of the DC bus voltage setting, I is the output current of the unit converter, k is the sag curve coefficient, which indicates the slope.

Conventional sag control has some limitations, especially in systems with high cable impedance. The cable impedance affects the accuracy of current distribution. Suppose two power units have the same output power and set the same virtual impedance, but due to the different cable impedance, the I-U curves of the two converters are not the same sag curve when they actually run. In this case, the deviation of the current distribution will be different from the deviation of the DC bus voltage setting [7].

In order to solve the limitations of the traditional sag control, researchers have proposed various improvement strategies, including the compensation of the longitudinal intercept of the sag curve and the adjustment of the sag curve coefficients [8].

3.1.1 Sag curve intercept compensation

An Huy et al. proposed an improved sag control strategy for DC microgrids based on compensated intercept voltage, aiming at solving the voltage and power distribution imbalance problem existing in the traditional sag control [9]. The structure of the DC microgrid in this study as well as the two energy storage systems are shown in Fig. 2.

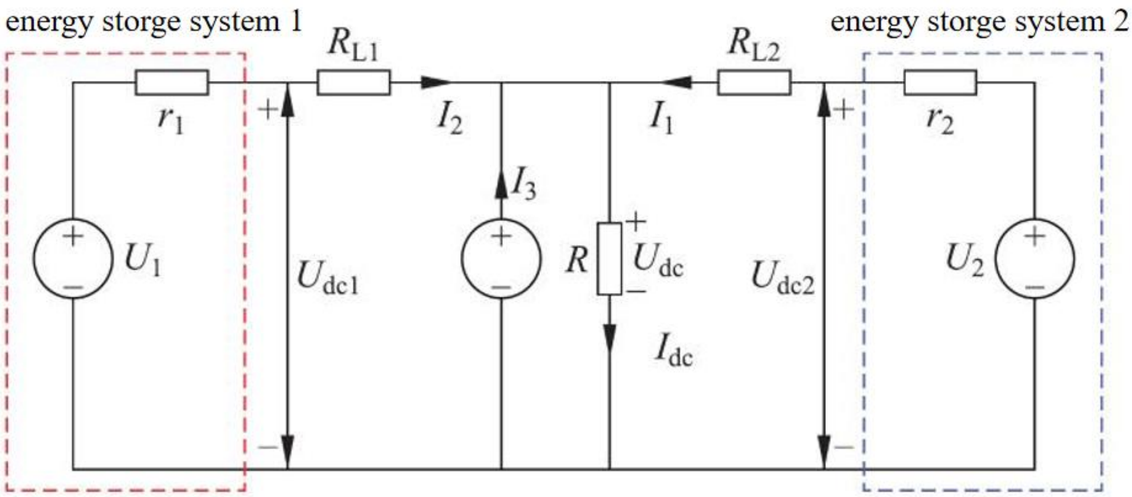

Fig. 2 DC microgrid equivalent circuit

The method improves the power quality and stability of the system through two levels of voltage compensation, the first level for improving the converter shunt accuracy and the second level for reducing the voltage deviation.

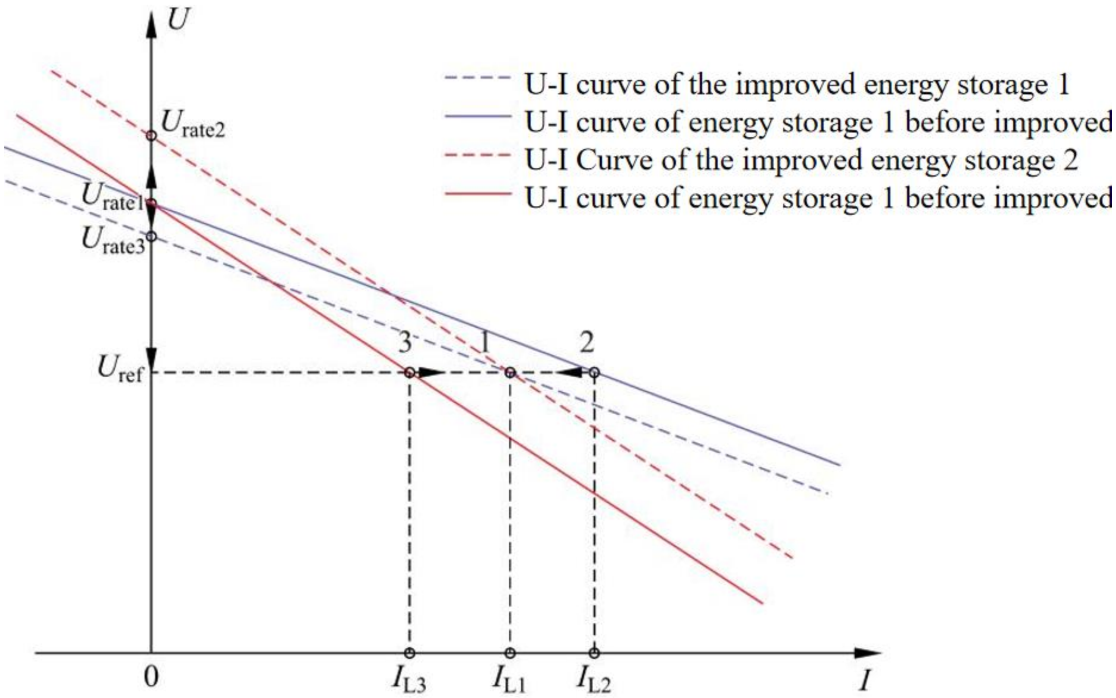

Fig. 3 Principle of the first stage compensation link

Fig. 3 illustrates the principle of the first stage of the improved sag control link. In this figure, the uneven power distribution due to the difference in line impedance can be reduced by adjusting the desired value of output voltage Urate for different energy storage devices. The curves with different colors represent the energy storage devices under different line impedances, and the reduction of power deviation can be achieved by the first-stage compensation link even under different line impedance conditions.

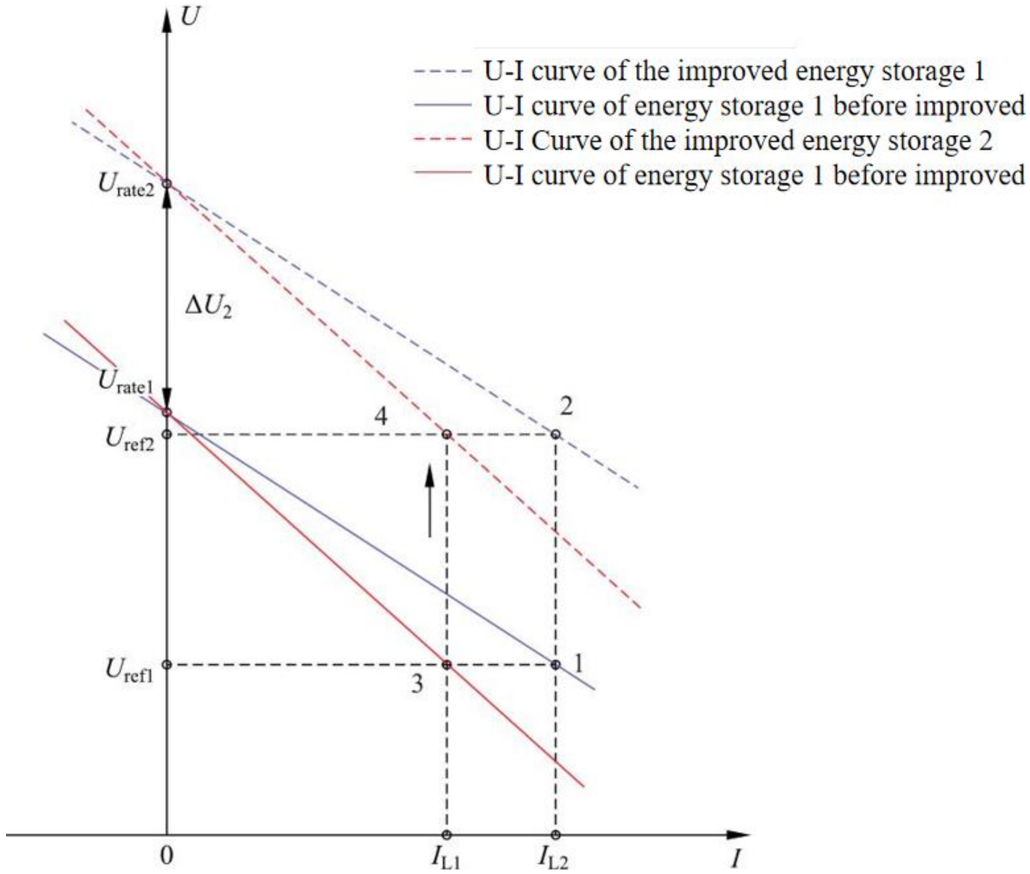

Fig. 4 Principle of second stage compensation link

Fig. 4 illustrates the operation of the second stage of the improved sag control link. The figure illustrates how the U-I curve of the energy storage system can be adjusted to shift upward by introducing a compensating intercept voltage ΔU2 to reduce the bus voltage deviation. When the operating point of the energy storage system is shifted upward due to the compensation, the output voltage Uref of the converter can be made close to the desired value Urate, realizing more accurate bus voltage control.

3.1.2 Sag curve factor adjustment

In order to solve the problem of large voltage and frequency fluctuations in conventional sag control, researchers also proposed a segmented hysteresis loop sag control strategy. This method sets different sag coefficients in different power output ranges, realizing the limitation of frequency and voltage fluctuation ranges while maintaining large sag coefficients. After adjusting the sag coefficients, reliable and stable operation of the microgrid can be ensured in both grid-connected and islanded states.

3.2. Virtual Synchronizer Technology Analysis

VSGs can be equated to controlled current sources and controlled voltage sources, so they can be categorized into current-type VSGs and voltage-type VSGs, but the former is weakly supportive for voltage and frequency, and has no islanding capability, so only voltage-type VSGs are studied here.

3.2.1 Analysis of traditional VSG technology applications

The applications of VSGs in microgrids are mainly in the following aspects:

Firstly, VSG can provide virtual inertia to enhance the system's resistance to disturbances. Secondly, through the virtual damping in it, system power oscillations can be reduced. Seamless switching can also be realized to adapt to the flexible conversion of grid-connected and islanded operation modes. And lastly, the combination of VSG and energy storage system can reduce the frequency deviation.

In practice, sag control can also be used in combination with VSGs to achieve better microgrid control. For example, in an islanded microgrid, the VSG can provide the necessary frequency support, while the sag control is responsible for the daily power allocation. In addition, the introduction of VSG can improve the power circulation problem that may occur in sag control, and through the principle of the interaction between virtual impedance and power loop, more accurate power regulation can be realized and the stability of independent power generation can be improved.

3.2.2 Improved VSG control strategy

Fangying Zhu and colleagues introduced an enhanced virtual synchronous generator (VSG) strategy, tailored to tackle the stability and precision issues of distributed generation units (DGs) in microgrids under power oscillations and high-frequency disturbances [10]. Voltage and angular frequency stability of DGs in microgrids is crucial for the system's reliable performance. However, traditional VSG control methods fall short in providing adequate inertia for voltage and frequency, making the system vulnerable to voltage and frequency swings during power changes, which negatively affects the microgrid's overall stability and power quality [10].

In order to overcome these difficulties, the following key improvements are introduced in the research results of Fangying Zhu et al: Coupling Compensation: the coupling compensation mechanism proposed in the study effectively reduces the uncontrollable coupling effect between different DGs due to power fluctuations by introducing an additional compensation term in the control strategy. This compensation not only improves the freedom of power regulation, but also enhances the robustness of the system to external perturbations.

Improved Torque Governor: an inertia link is introduced in the governor design, which is expressed by the following mathematical formula:

$$\omega_s = \omega + \frac{1}{J_s}(T - T_{ref}) \tag{4}$$

Where ω_s stands for the angular frequency of the system after considering the inertia, J_s is the inertia factor, T and T_{ref} are actual torque and reference torque, respectively. This design allows the system to adjust its output more gently in the face of power fluctuations, reducing voltage and corner frequency fluctuations.

Improved Excitation Control: The excitation control system is also improved to introduce voltage inertia, which helps to maintain voltage stability when the system is disturbed. By adjusting the excitation control parameters, the dynamic response of the system can be optimized to improve the voltage stability.

Sag control Characteristics: In the improved control strategy, finer regulation of active power is achieved by introducing sag control. The mathematical expression for sag control is:

$$P_{ref} = P + k_{e\omega}(\omega_{ref} - \omega) \tag{5}$$

Where P_{ref} is the reference active power after taking into account the sagging characteristics. $k_{e\omega}$ is the sag factor, which adjusts the active power output based on the deviation between the actual angular frequency ω and the reference angular frequency ω_{ref} of the system.

Together, these improvements significantly enhance the stability and regulation accuracy of the microgrid when facing various operating conditions. Through experimental validation, Fangying Zhu et al. demonstrate the significant effect of their control strategy in reducing power fluctuation and improving system stability. Specifically, compared with the conventional VSG control strategy, the improved strategy reduces the active power circulating current from 112 W to 38 W and the reactive power circulating current from 95 VAR to 26 VAR during parallel operation. In addition, the maximum overshooting amplitude of voltage and frequency is effectively controlled from more than 2% to less than 0.5% when the DGs are connected or disconnected [10]. These quantitative improvement results not only prove the effectiveness of the new control strategy, but also provide strong technical support for the stable operation and control of the microgrid.

4. Future challenges and perspectives

The extensive integration of renewable energy sources like solar and wind into microgrids introduces greater stability challenges. A high penetration rate signifies an escalating count of distributed power sources connected to the grid, potentially resulting in more pronounced voltage and frequency oscillations and exacerbating the system's instability [11]. Therefore, future research on inverter control strategies should focus on how to maintain stable operation of microgrids under high penetration rates to improve the quality of power supply from independent power generation.

Energy storage devices are an important part of microgrids. In the context of independent power generation, the energy storage system is capable of fulfilling two distinct yet interrelated functions. Firstly, it serves to provide energy reserves, and secondly, it is able to achieve a state of equilibrium between supply and demand through the regulation of the charging and discharging process. Currently, the energy storage system still needs to be optimized, and future research should focus on how to manage the energy storage system more efficiently, which not only improves the stability of power generation under high penetration, but also increases the energy efficiency and economy of the whole microgrid.

The application of virtual synchronous machine (VSG) technology in microgrids has demonstrated superiority through validation by researchers, especially in providing virtual inertia and virtual damping. However, there are still many issues that need to be addressed in the practical application of VSG technology, such as how to more accurately model the characteristics of synchronous generators and how to better integrate it with other control strategies, such as sag control. In future research, the control algorithm of VSG can be further optimized to improve its adaptability and reliability in microgrids.

Given the centrality of sag control in existing research, future research could also continue to explore how to further optimize the sag control strategy and how to integrate it with other advanced techniques such as artificial intelligence and machine learning algorithms to achieve a more efficient and smarter microgrid management system.

5. Conclusion

This paper synthesizes and analyzes current literature and research results to provide insight into the central role of sag control in independent power generation in microgrids. Sag control is indispensable in many researches because it provides a simple, efficient and easy-to-implement distributed control strategy that allows inverters in a microgrid to autonomously respond to grid variations and achieve a balanced distribution of power while maintaining voltage and frequency stability. In addition, the flexibility and adaptability of sag control makes it compatible with a variety of microgrid operation modes, including islanding and grid-connected modes. With the development of technology, sag control strategies are continuously optimized and combined with other advanced technologies such as virtual synchronous generators (VSGs) to further improve the stability and power quality of microgrids. Therefore, sag control occupies an indispensable position in the research and development of microgrid control technologies and is a key factor in driving the realization of more efficient and reliable energy systems.

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