Recent Progress in the Stability of Internal Control Systems for Photovoltaic Power Systems

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Abstract. In the context of the new era, the development of renewable energy is of great significance. Its utilization not only alleviates energy shortages but also significantly reduces environmental pollution. With the widespread application of digital technology in the power system, higher demands are placed on the operational stability of power control systems to enhance energy storage capacity and cope with unstable factors such as voltage and current fluctuations. This paper focuses on the key internal links of photovoltaic power generation systems and focuses on the control strategies of battery energy storage and power generation devices, using representative control methods such as PID control and model predictive control (MPC), systematically analyzes the applicability and advantages and disadvantages of different control methods in each link, and then proposes optimal control schemes for each part. Based on this, an overall control system for the photovoltaic power generation system is constructed, providing theoretical support and technical paths for the efficient and stable operation of the system.

Keywords: Photovoltaic Power Generation, Battery Energy Storage, Power Generation Devices, Control System.

1 Introduction

Control systems are widely used in the power industry. The difficulty in photovoltaic power generation is that it is greatly affected by light intensity and temperature, especially during the day when the sunlight is strong, the power output of photovoltaic is large, which may cause distribution network to exceed the normal range, posing a potential safety risk to equipment and users. When the light weakens, the power generation drops sharply, and the voltage drops accordingly. This leads to frequent fluctuations in voltage at distribution network nodes.

A photovoltaic (PV) system is a renewable energy system that converts solar energy directly into electricity without the need for mechanical devices. It has the advantages of simple structure, long lifespan and stable operation. It can be flexibly adapted to different power levels and is often used in independent power supply scenarios [1]. In remote areas, the rational design of the scale of the power supply system is particularly

S. Zhang (ed.), *Proceedings of the 2025 International Conference on Electronics, Electrical and Grid Technology (ICEEGT 2025)*, Advances in Engineering Research 292,
https://doi.org/10.2991/978-94-6463-986-5_81

important for achieving economically efficient power generation. Therefore, photovoltaic and other renewable energy systems are preferred options for medium and low power applications. In China, photovoltaic power generation technology has matured, and significant progress has been made in expanding battery materials from monocrystalline silicon and polycrystalline silicon to a variety of semiconductor materials. Spain once led the global photovoltaic market with 2.6 GW of new grid-connected capacity, pushing the global market to grow annually to 5600 MW, doubling from 2007; But the market size shrank by more than 80 percent (about 2100 MW) after the 500 MW installation limit was implemented in 2009. Germany, with the help of geographic information system (GIS) and laser scanning technology, combined with building floor plan data, has developed algorithms that can identify suitable roof areas and extract key parameters such as roof shape, inclination and orientation [2]. In addition, in terms of control methods, the most fundamental control method in photovoltaic power generation is proportional-integral (PI) control, which effectively eliminates steady-state errors by introducing an integral link to regulate and improve system response performance [3].

This paper first conducts an in-depth analysis of the composition structure of different types of power control systems to clarify their functional division and operational characteristics; Secondly, the different effects of various control technologies on system stability are explored, revealing the correlation mechanism between key technical parameters and system dynamic performance. Finally, for different application scenarios, schemes for choosing the optimal control strategy were proposed to achieve the synergistic improvement of system stability and adaptability. This study can provide a theoretical reference for the problem of insufficient stability in photovoltaic power systems and has significant engineering practice significance and application value.

2 Principles and Control of Energy Storage in Photovoltaic Cells

2.1 Photovoltaic Cell Energy Storage Principles

Photovoltaic cells can be classified according to the type of material used. Monocrystalline silicon solar cells have high photoelectric conversion efficiency and long service life, but they are relatively expensive to manufacture; Polycrystalline silicon solar cells are relatively less costly, but their conversion efficiency and lifespan are slightly lower than those of monocrystalline silicon. Amorphous silicon solar cells, due to their lightness, flexibility and weight, are suitable for some specific scenarios; Copper indium gallium selenide (CIGS) solar cells have the potential to achieve higher conversion efficiency because of their smaller bandgap [4].

At present, most solar cells use the PN structure. As shown in Fig.1, the P-type semiconductor has a higher concentration of holes, while the N-type semiconductor is rich in free electrons. When they come into contact, a PN junction is formed at the interface. In the PN junction region, electrons recombine with holes and build an inbuilt electric field. This electric field can effectively separate the electron-hole pairs produced by light, causing the electrons to flow directionally along the external circuit, thereby generating a current, which is the output current of the photovoltaic cell; The output voltage is determined by the built-in potential of the PN junction [5].

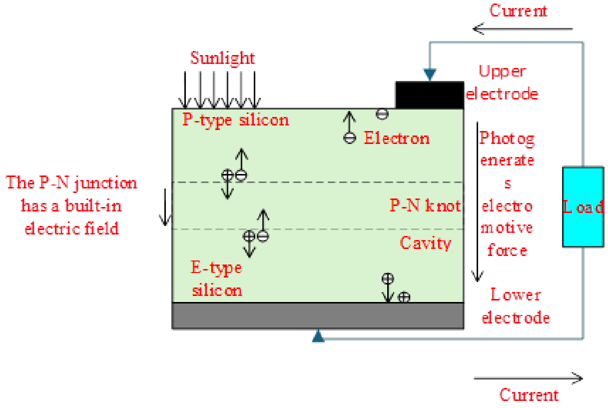

Fig. 1 Schematic diagram of photovoltaic cells.

2.2 Theory of Control Methods for Photovoltaic Cells

The common control methods for photovoltaic storage systems mainly include PID control, fuzzy control and model predictive control (MPC), etc. PID control regulates the input through proportional, integral, and differential operations to stabilize the output and keep the system operating within a predetermined range of voltage and current. The fuzzy logic-based controller is suitable for light uncertainty and system nonlinearity characteristics. When the battery discharge environment changes, it can respond quickly to voltage fluctuations and, in combination with optimization algorithms, achieve dynamic adjustment of charging and discharging strategies for optimal energy management optimization. At the same time, overcharge and over discharge protection can prevent the battery from operating beyond its limit and extend its lifespan. MPC is particularly suitable for handling multiple-input multiple-output (MIMO) systems by constructing system models to predict future behavior and thereby generating optimal control sequences. Although multiple PID controllers are also applicable to MIMO systems, due to the coupling between control loops, parameter adjustment is difficult and control effect is limited [5]. In contrast, MPC controllers have the advantages of simple structure, strong adaptability and low computational cost, and are suitable for photovoltaic storage systems in complex operating environments.

3 Power generation Systems and Control Theory

3.1 Types of Photovoltaic Power Generation Systems

In today's world, stand-alone photovoltaic systems and grid-connected photovoltaic systems are the mainstream types of photovoltaic power generation systems.

Stand-alone PV systems consist of solar photovoltaic arrays, energy storage devices, charging controllers, power electronic converters, etc. Solar energy is converted into electricity through the photovoltaic array immediately, then transformed by the power electronic converter to supply power to the grid, and the excess electricity is stored in the energy storage device in the form of chemical energy after passing through the charging controller. Therefore, energy storage components are of the utmost importance in an independent photovoltaic system.

Grid-connected photovoltaic systems consist of photovoltaic arrays, high-frequency DC/DC boost circuits, power electronic converters (inverters), and system monitoring components. The system works by converting solar radiation energy through photovoltaic arrays into electrical energy, then converting high-frequency direct current into high-voltage direct current, and then inverting through inverters to output sinusoidal alternating current consistent with the grid voltage. The difference between the two systems is that grid-connected photovoltaic power generation systems are directly connected to the grid, so the surplus of the photovoltaic array can be complementary to the parallel grid, eliminating the energy storage components such as batteries that are necessary in independent photovoltaic power generation systems.

3.2 Control Methods for the Power Generation System

The control methods for power generation systems are more complex. A technology designed to achieve maximum power, known as Maximum Power Point Tracking Technology In this situation, the maximum power point will shift as the weather and the duration of sunlight change from day to day. In addition, the characteristic of the maximum power point tracking system is that it adjusts the system according to the maximum power point at any time. Common implementation methods include: (1) Perturbation observation method. This method involves periodically, in small increments, perturbating the output voltage of the photovoltaic cell and observe the changes in power. The power will change direction along with the variations in the disturbance [4]. Incremental derivative method. The method determines the position of the current operating point by comparing the derivative of the photovoltaic cell (the ratio of current to voltage). The system reaches its maximum power point when the derivative is zero, increases the voltage when the derivative is greater than zero, and decreases the voltage when the derivative is less than zero. This technology can track the output status of the photovoltaic cells in real time and dynamically adjust the operating point of the circuit to improve conversion efficiency.

The second is grid-connected control. The grid-connected inverter is capable of performing the task of converting direct current to alternating current. Its core function is to convert direct current into alternating current with the same frequency and voltage as the grid, and it can operate in parallel with the public grid [6]. Negative feedback control is also used to ensure that the output voltage of the inverter meets the requirements of the power grid. When the power station is connected to the grid, it is necessary to ensure grid frequency modulation to ensure the stability of grid frequency. The advantage of this technology is that it can be directly complementary to the grid, reducing power transmission losses.

The third is inverter control, which adjusts the output voltage to control the transmission of power. As can be seen from Fig. 2, this control method uses control algorithms such as PID controllers and proportional-integral (PI) controllers to achieve precise regulation of the output current. The control strategy includes voltage feedback control, which can adjust the voltage at any time to keep it at a safe level to maintain the stability of the grid voltage [7]. The PID controls the power with the aim of adjusting output, which can reduce reactive power in the grid. Inverters also need to be adjusted when light and circuit loads change to maintain system safety, such as dynamic voltage recovery and rapid power regulation, to ensure stable operation of the system under transient disturbances.

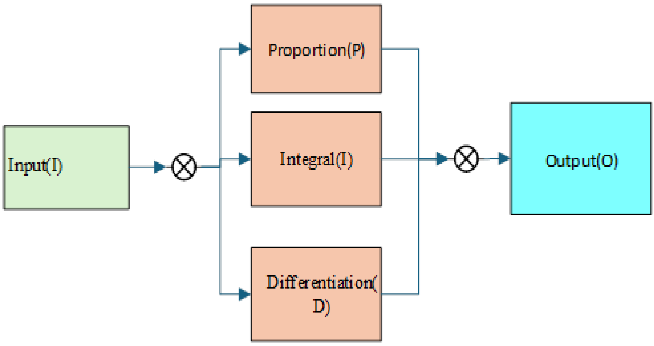

Fig. 2 PID control method.

4 The Best Composition of a Photovoltaic System

A large amount of photovoltaic power generation connected to the grid may cause the distribution network voltage to exceed the normal operating range, which will affect the safety and stability of the distribution network. The control effect of traditional single active and single reactive voltage control strategies is often limited and in most cases insufficient to meet the grid connection requirements of distributed photovoltaics. In rainy and cloudy weather, the reduced efficiency of photovoltaic power generation may lead to instability in power supply and a decline in power quality [7].

MPC has obvious advantages in terms of control effect, especially for handling multi-input multi-output systems, but it has high requirements for the accuracy of the system model, and establishing an optimal model increases costs and system complexity [8]. In contrast, PID control is simple and cost-effective, requiring only three parameters to adjust, and is suitable for general application scenarios. However, when dealing with complex systems, the parameter tuning difficulty of PID control under multivariable coupling increases significantly, limiting its control accuracy.

Grid-connected technology can be divided into voltage control mode and current control mode based on the control target of the inverter, and a balance should be struck between cost, system complexity and control performance when choosing. PID control systems are typically regulated based on a single amount of feedback, and the controller form can be flexibly adjusted according to the feedback type. It is suitable for situations where stability requirements are low or the system structure is relatively simple.

For individual users with low electricity demand and difficulty in achieving high control costs, a core control strategy that focuses on energy storage optimization management can be chosen, combining the PID control method with maximum power point tracking technology (MPPT), which ensures stable charging and discharging of the energy storage system and improves the power generation efficiency of photovoltaic modules to meet basic power supply requirements [9]. For grid-connected photovoltaic systems, a combination of MPC and grid-connected control can be chosen. MPC is suitable for handling multi-input and multi-output systems with high control accuracy, and grid-connected control helps with power transmission and regulation, reducing power loss [10]. When the control objective is to keep parameters such as voltage and current within the set range, PID can be used as the basic control method, or PID control can be introduced on both sides of the master-slave control structure [11]. Based on the above scenario analysis, Table 1 summarizes the advantages and disadvantages of each control method.

Table 1 takes into account the performance characteristics of different types of power generation systems, and their control methods show different advantages and disadvantages in practical applications. The corresponding control strategies vary in response to the problems faced by each type of system. The following table lists the main advantages and disadvantages of common control methods.

Table 1. Advantages and Disadvantages of Different Types of Control Methods.

Control methods	Advantages	Disadvantages
PID control	Adapt to complex charge and discharge scenarios	There are coupling relationships, and parameter adjustment is difficult
Model Predictive Control (MPC)	The cost of building a system is low, and the system is not overly complex	Control performance is overly dependent on the accuracy of the system model
Maximum power tracking control	Quick response, boost conversion efficiency	The algorithm is complex and the system design is difficult
Grid connection control	Synchronize with the city grid to reduce power transmission losses	Weak current networks are prone to instability and have weak harmonic suppression capabilities
Control methods	Advantages	Disadvantages

In conclusion, the control strategy of photovoltaic power generation systems should be selected in combination with specific application scenarios. This paper suggests giving priority to the technical adaptation based on the actual available resources and performance targets, seeking a balance between economy and stability, and achieving a reasonable adaptation and optimal configuration of control technologies.

5 Conclusion

This paper examines the adaptation methods of the internal control system of photovoltaic power generation systems and more efficient control schemes, with a focus on analyzing the impact of control system stability on the overall performance of photovoltaic systems. Based on a brief review of the current development status of control stability in photovoltaic systems, it is pointed out that with the continuous transformation of the global energy structure and the wide application of renewable energy. It is pointed out that with the transformation of the global energy structure and the large-scale application of renewable energy, the stability of the internal control system of photovoltaic power, as an important component of clean energy, directly or indirectly guarantees the safety, generation efficiency and output quality of the power system.

In addition, this paper explores the stability of internal control in photovoltaic power systems from multiple dimensions, covering key links such as energy storage device control, power generation side control, and grid connection control. By introducing advanced control algorithms such as model predictive control (PC), maximum power point tracking technology (MPPT), etc., researchers have made significant progress in effectively improving the challenges of high dynamics and nonlinearity in photovoltaic power generation, and effectively enhancing the operational efficiency and robustness of the system.

In summary, this paper provides a reference for different application scenarios, has important reference significance for designing cost-effective power control systems, and is of great significance for promoting the popularization of photovoltaics (especially in low-resource scenarios) and grid stability.

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