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A Review of Maximum Power Point Tracking Control Strategies for Photovoltaic Power Generation Systems

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Abstract. Amid the worldwide shift toward new energy, PV power generation, being a vital part of clean and renewable energy resources, has its efficient and stable operation regarded as essential for enhancing the energy mix and driving sustainable development. However, the output power of PV cells is influenced by the nonlinearity of environmental factors such as light intensity and temperature, which poses challenges to the power generation efficiency of PV cells and leaves room for further improvement. This paper comprehensively outlines the operational principles and mathematical modeling of PV power generation systems and their key component, the PV cell. It also delves into the mechanisms, benefits, and constraints of both traditional and intelligent MPPT algorithms. In addition, this paper also discusses the MPPT algorithms under special application scenarios. In the future, MPPT technology will integrate deep learning, artificial intelligence and other cutting-edge technologies to explore the control mode of synergistic optimization with new photovoltaic materials and high-efficiency energy storage systems, which is expected to promote the maximum power point tracking control technology of photovoltaic power generation system to a higher level, and help the global energy transition and sustainable development.

Keywords: Photovoltaic power generation system, Maximum power point tracking (MPPT), Control strategy

1. Introduction

As the global energy crisis intensifies and environmental concerns become more pressing, photovoltaic power generation, as a clean and renewable energy source, has garnered significant global attention. The electricity production of photovoltaic is cells frequently influenced by several factors such as the intensity of light, temperature and other non-linear behaviors. Therefore, to boost the efficiency and economy of photovoltaic power generation systems, researchers both domestically and internationally have dedicated themselves to enhancing the control strategies and algorithms of such systems. By fine-tuning the controllers, they aim to operate the photovoltaic arrays at their maximum power points, which involves maximum power point tracking control, thereby achieving optimal power output from the photovoltaic systems. The MPPT control strategy ensures that PV panels across diverse operating environments consistently stay near their maximum power point. This not only enhances the PV power system's overall efficiency and output quality but also minimizes PV panel waste, boosts solar cell utilization, and cuts energy consumption and costs.

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In this paper, we will investigate the maximum power point tracking control strategy for PV power systems and examine the methods and technical solutions to address the issues in existing research.

2. Photovoltaic power generation systems and the working principle of photovoltaic cells

2.1. Components of a photovoltaic power generation system

A complete photovoltaic (PV) power generation system is mainly composed of PV arrays, DC-DC circuits, maximum power point tracking controllers, inverters, battery packs and loads [1]. Among them, the PV cell array is the core part of the system, the PV cells are placed according to certain rules to form modules, and then the PV modules are connected in port and series through parallel diodes to form the PV array, which is responsible for converting the sunlight energy into DC energy. The role of the DC-DC circuit is to transform a certain level of DC power into another level of DC power. The maximum power point tracking controller is used to adjust the operating state of the PV cells in real time to ensure that their output power is maximized. The role of the inverter is to invert the DC power generated by the PV into AC power to meet the demand of the load or to be connected to the grid. The main function of the battery bank is to complete the coordinated control strategy for energy storage, which can provide power support for the load when there is insufficient light.

2.2. Mechanism of operation of photovoltaic cells

In a photovoltaic power generation system, the photovoltaic cell serves as the fundamental building block and the means to achieve the conversion of solar energy. Photovoltaic cells work based on the photovoltaic effect of semiconductor PN junctions. When sunlight hits the semiconductor material, the photons with sufficient energy are absorbed. This absorption energizes the electrons within the semiconductor, enabling them to break free from their atomic bonds. Consequently, the material's electron-hole pairs are split up. Under the influence of the built-in electric field of the PN junction, electrons flow toward the N region and holes toward the P region. This movement creates a potential difference across the PN junction and generates a DC current. By connecting the load through the external circuit, the electrons can flow to the P region through the external circuit, which can realize the output and utilization of electric energy.

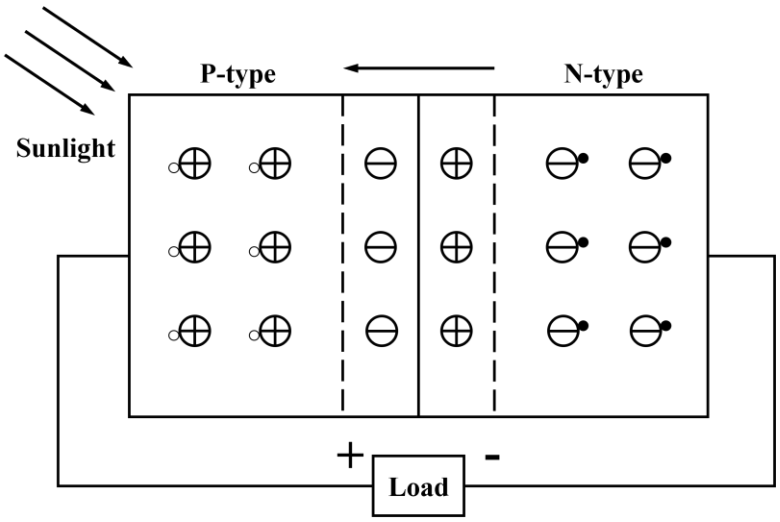

Figure 1: Photovoltaic cell working principle diagram

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2.3. Mathematical modeling of photovoltaic cells

The mathematical model of a PV cell provides a foundation for analyzing its output characteristics. Commonly used models are the single diode and double diode models. The single diode model takes into account the series and shunt resistances of the photovoltaic cell. The equivalent circuit of the photovoltaic cell is depicted in Figure 2, which includes the following equations for the I-V characteristic [2]:

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V+IR_s}{\alpha V_t} \right) - 1 \right] - \frac{V+IR_s}{R_p} \tag{1}$$

where Iph is the photogenerated current, I0 is the diode reverse saturation current, Rs is the series resistance, Rp is the shunt resistance, α is the diode ideality factor (1≤ α≤2), and Vt =kT/q is the thermoelectric voltage where k is the Boltzmann's constant, T is the temperature of the cell (°F), and q is the electron charge.

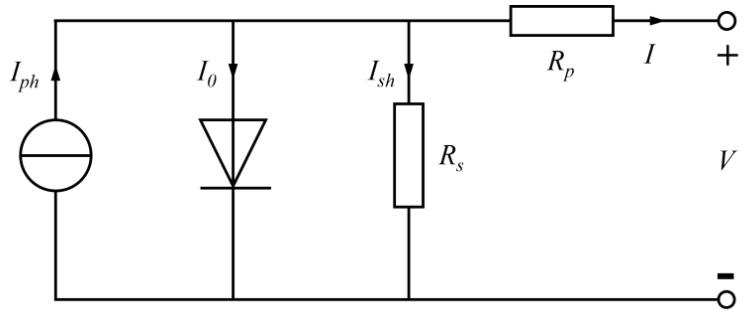

Figure 2: Photovoltaic cell equivalent circuit diagram

The model can accurately describe the output characteristics of photovoltaic cells under different light intensity and temperature conditions, providing a theoretical basis for the design of MPPT algorithm and system performance analysis.

3. Tracking control algorithm for maximum power point

As a key component of photovoltaic power systems, the performance of the MPPT algorithm directly determines the system's power generation efficiency and economic viability. On the basis of its principle and implementation, the MPPT algorithm is grouped into two types: conventional and intelligent MPPT algorithms.

3.1. Traditional MPPT algorithm

3.1.1. Perturbation observation (P & O)

As one of the oldest and most widely adopted traditional MPPT algorithms, the perturbation and observation method operates by consistently introducing small perturbations to the PV system's operational voltage. It then assesses the power variation direction to dictate the subsequent perturbation’s course. If the power shows an increasing trend, the perturbation continues in the original direction; otherwise, the perturbation direction is adjusted. This is repeated until the maximum power point is found. The advantage is that the realization process is relatively simple and easy to carry out low-cost hardware implementation in practical applications. However, the method

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is prone to steady-state oscillations near the maximum power point, resulting in partial power loss, and the tracking speed may not meet the demand when the environmental conditions change rapidly. Therefore, this algorithm is more suitable to be applied in PV power generation scenarios that are cost-sensitive and have relatively loose requirements on tracking speed and accuracy [3]. As Fig. 3 shows the flowchart of the perturbation observation method.

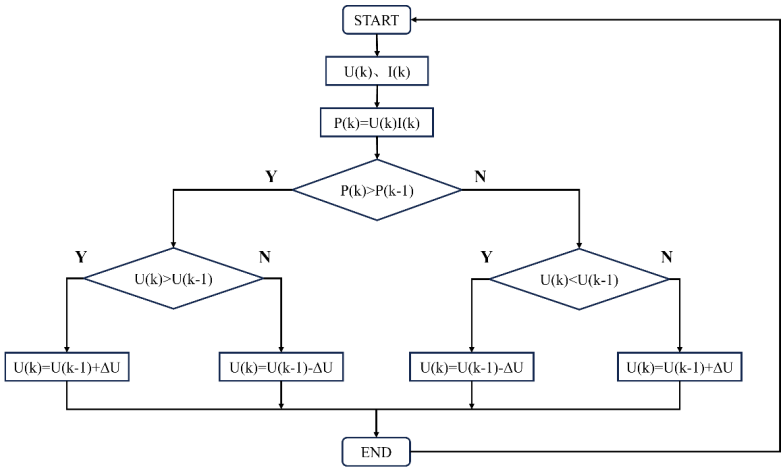

Figure 3: Perturbation Observation (P&O) flowchart

3.1.2. Conductivity increment method

The conductance increment approach relies on the output characteristics of the PV cell. By analyzing the instantaneous conductance and its variation, it assesses the position of the current operating point relative to the maximum power point. At this maximum power point, the power meets the condition P=UI , and upon differentiation [2], this relationship yields:

$$\frac{dP}{dU} = \frac{d(UI)}{dU} = I + U\frac{dI}{dU} \tag{2}$$

Where P is the PV output power and U is the output voltage. The tracking of the maximum power point can be realized by its differentiation result, and the judgment is based on the following:

$$\begin{cases} \frac{dP}{dU} < 0, \ To\ the\ Right\ of\ the\ MPP \\ \frac{dP}{dU} = 0, \ At\ the\ MPP \\ \frac{dP}{dU} > 0, \ To\ the\ Left\ of\ the\ MPP \end{cases} \tag{3}$$

Therefore, by determining the sign of I/U+dI/dU, i.e. G+dG (G is conductance), it can be ascertained whether the PV array operates at its maximum power point.

The conductivity increment method can provide higher tracking accuracy to some extent and may have an advantage in terms of speed of response to environmental changes compared to the perturbation observation method. However, its more complex implementation requires more computational power and higher sensor accuracy, which undoubtedly increases the overall cost of the system. Therefore, the conductivity increment method is more suitable to be applied in PV power generation systems that require high tracking accuracy and relatively loose cost control[3].

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3.2. Intelligent MPPT algorithm

3.2.1. Methods based on optimized mathematical models

As mathematical modeling and optimization techniques progress, MPPT strategies using refined mathematical models are gaining growing interest in research. This approach, which builds a precise mathematical model of the PV system and uses sophisticated optimization algorithms to identify the maximum power point, can greatly enhance tracking accuracy and speed. In the intricate and variable environmental conditions, it reveals distinctive benefits. For example, with the help of iterative algorithms, the unknown parameters in the equivalent circuit model of photovoltaic power generation are solved accurately, and a mathematical model of the photovoltaic array covering the full range of operating conditions is established, which lays a more precise theoretical foundation for maximum power point tracking. [4]. Additionally, this method can holistically account for the impact of light intensity, temperature, and other factors. This enables precise prediction of the maximum power point's location and robustly ensures the PV power generation system's efficient operation.

3.2.2. Perturbation-based self-optimization

Based on the traditional perturbation observation method, researchers have deeply improved and optimized it by introducing an innovative self-optimization mechanism. For example, the particle swarm optimization (PSO) algorithm is introduced into the MPPT process, and the perturbation step size is automatically adjusted according to the real-time operation status of the system, thus significantly improving the tracking performance. This MPPT method based on perturbation self-optimization not only effectively reduces the steady-state oscillation phenomenon, but also completes the tracking task of the maximum power point with faster speed and higher accuracy. By intelligently adjusting the perturbation strategy, the system is able to better adapt to the environmental changes and avoid the problems of low tracking efficiency caused by the fixed step-size perturbation, which provides a more reliable control means for the stable operation of PV power generation systems in complex environments [5].

3.2.3. Methods based on intelligent processing methods

Amid the rapid advancement of artificial intelligence technology, MPPT strategies that utilize intelligent processing methods have surfaced and garnered significant attention and adoption in recent years. For example, intelligent algorithms such as gray wolf optimization algorithm (GWO) and ant colony optimization algorithm (ACO) are successfully applied in the field of maximum power point tracking. As an example, GWO mimics the pack hunting behavior of gray wolves to boost the MPPT controller's global and local search capabilities. This approach effectively addresses the uncertainty in the PV system's output power, enabling the rapid and precise identification of the global maximum power point, and thereby substantially enhancing the efficiency and stability of the PV power generation system [6]. Moreover, the integration of the ant colony optimization algorithm with a fractional-order nonlinear controller utilizes the algorithm's distinctive pheromone propagation and path search capabilities. This combination achieves effective maximum power point tracking for PV cells and further drives the intelligent development of photovoltaic power generation technology [7].

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3.2.4. Output-based control methods

By accurately adjusting the output of the PV system, effective tracking of the maximum power point can be achieved. For example, a novel digital control scheme that organically combines a power converter based on the voltage control method with a PI controller is used to adaptively perturb the input voltage reference value until the maximum power point is reached [8]. In addition, a novel variable step-size PV maximum power point tracking control strategy is proposed, which uses the rate of change of output power with voltage (P'(u)) as the key parameter and dynamically adjusts the perturbation step size, thus significantly improving the tracking speed and efficiency while ensuring the tracking accuracy. By directly controlling the output of the system, this approach not only enhances the stability of the system, but also effectively reduces the energy loss and improves the overall performance of the photovoltaic power generation system [9].

3.3. MPPT algorithm for special application scenarios

In some specific application scenarios, such as temperature and humidity power supply systems for greenhouses in agricultural facilities, PV systems need to cope with more complex geographic and usage environments. For this reason, researchers have developed MPPT algorithms that are specifically applicable to these scenarios. For example, a fuzzy-conductance incremental MPPT algorithm is proposed by deeply integrating the fuzzy control technique with the conductivity incremental method. Experimental results show that the algorithm not only effectively improves the output efficiency of the system, but also better meets the power supply requirements of special scenarios such as agricultural greenhouses, demonstrating good adaptability and practicality [10]. Similarly, the multiverse optimization algorithm (MVO) and its improved version have been widely used in distributed generation systems to cope with the multi-peak problem caused by partial shading effect. By simulating the multiplicity and evolution process of the universe, the MVO algorithm can effectively search for the global maximum power point under complex multi-peak power - voltage curves, thus ensuring the efficient operation of the distributed generation system, and providing a new idea and method for solving the partial shading problem[11].

4. Concluding remarks

The MPPT control strategy for PV power generation systems is a vital technique to enhance the efficiency and cost-effectiveness of PV power generation. As PV power generation technology advances, research on MPPT control strategies will encounter more stringent demands and novel challenges. Moving forward, we can incorporate cutting-edge technologies like deep learning and artificial intelligence to uncover potential performance improvements in PV systems. We'll also investigate MPPT control models optimized with novel PV materials and efficient energy storage systems. Additionally, we'll intensify empirical studies in scenarios such as complex climate conditions and large-scale PV power station clusters. These efforts aim to elevate PV power generation's MPPT control technology and support the global shift towards sustainable energy. The research will assist the worldwide shift toward sustainable energy and development.

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