Postprint: Research on Maximum Power Point Tracking for Photovoltaic Power Generation Systems Based on Combined Fuzzy Control and Adaptive Step Size

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Abstract

Photovoltaic power generation has been increasingly recognized and adopted. Based on the nonlinear output characteristics of photovoltaic cells, a fuzzy control methodology is employed for maximum power point tracking (MPPT). This paper establishes a simulation model of the photovoltaic power generation system, designs a fuzzy controller, and implements an adaptive step-size adjustment method to automatically regulate the controlled variable, thereby compensating for the deficiencies of conventional step-size algorithms in MPPT for photovoltaic systems. Through comparative analysis with simulation results of traditional fixed step-size and variable step-size approaches, it is demonstrated that the fuzzy control-based adaptive step-size adjustment method can rapidly achieve MPPT control for photovoltaic power generation systems while maintaining stable output.

Full Text

Preamble

Research on Maximum Power Point Tracking of Photovoltaic Generation Systems Based on Fuzzy Control and Adaptive Step Size Combination

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Abstract

Photovoltaic power generation has gradually gained widespread attention and adoption. Given the nonlinear output characteristics of photovoltaic cells, this paper employs a fuzzy control method for maximum power point tracking (MPPT). A simulation model of the photovoltaic power generation system was developed, and a fuzzy controller was designed. To address the limitations of traditional step-size algorithms in MPPT for photovoltaic systems, an adaptive step-size adjustment method was implemented to automatically regulate the controlled variables. Through comparative simulation with traditional fixed-step and variable-step methods, the results demonstrate that the fuzzy-control-based adaptive step-size adjustment approach enables rapid MPPT control for photovoltaic systems while maintaining stable output values.

Keywords: Photovoltaic power generation, maximum power point tracking, fuzzy control, adaptive step-size adjustment method

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2 MPPT Experimental Principles and Control for Photovoltaic Systems

Solar energy represents a novel green renewable energy source, and solar power generation is widely recognized as the cleanest form of electricity generation. The most significant challenge facing photovoltaic systems is the low photoelectric conversion efficiency of solar arrays, which ranges from only 12% to 17% [1]. Consequently, the maximum power point tracking (MPPT) problem in photovoltaic systems has become a focal point of research worldwide.

Current domestic and international research primarily focuses on achieving maximum power output by improving MPPT control algorithms for photovoltaic systems. Notable scholars such as Ge Lifang et al. proposed a fixed voltage method for MPPT, which operates based on the coupling relationship between the open-circuit voltage and maximum power point of photovoltaic cells to regulate the system operating voltage. While this approach offers the advantage of fixed output voltage and easy control, it cannot track the real-time output state of photovoltaic cells when external conditions change, resulting in significant power losses [2-3]. Ren Ling et al. introduced the perturbation and observation (P&O) method, which is simple to implement, requires few measurement parameters, and is currently the most commonly used MPPT algorithm [4]. Its principle involves introducing small perturbations to the system and observing the response to determine and adjust the output voltage direction, enabling the photovoltaic cell to reach the maximum power point. However, this method suffers from relatively low control precision and slow response, making it suitable only for stable environmental conditions [5-6]. Huang Yao et al. proposed the incremental conductance method for MPPT, which adjusts the operating voltage based on the relationship between the dynamic and static conductance values of the photovoltaic array output. This method can quickly detect sudden environmental changes and track accordingly to ensure stable operation, but its algorithm structure is relatively complex and difficult to implement [7-8]. This paper adopts fuzzy control [9] for MPPT in photovoltaic systems to compensate for the shortcomings of these traditional methods and achieve more satisfactory performance.

2.1 Photovoltaic System Principle and Composition

A photovoltaic power generation system primarily consists of photovoltaic cell modules, control circuits, an MPPT controller, and a load. Photovoltaic cells convert solar irradiation into electrical energy. The control circuit employs a DC-DC converter implemented as a boost chopper circuit [10]. The MPPT controller realizes its function through a combined algorithm of fuzzy control and adaptive step-size adjustment. The equivalent circuit diagram of the photovoltaic system is shown in [Figure 1: see original paper].

2.2 Photovoltaic Cell Modeling and Simulation

The photovoltaic cell model can be equivalent to a voltage source in parallel with a diode, with additional series and shunt internal resistances. The equivalent circuit is shown in [Figure 2: see original paper]. From this diagram, the relationship between the output current I and output voltage V of the photovoltaic cell can be derived as:

$$I = I_{ph} - I_d = I_{ph} - I_o \exp\left(\frac{q(V + R_s I)}{AKT}\right)$$

where I_{ph} is the current generated by the photovoltaic cell under illumination; I_o is the reverse saturation current; R_s and R_{sh} are the series and shunt resistances; T is the cell surface temperature (K); A is the ideality factor ($A = 1 \sim 2$); q is the electron charge (1.6×10^{-19} C); and K is the Boltzmann constant (1.38×10^{-23} J/K).

The reverse saturation current I_o can be expressed as:

$$I_o = I_{rr} \exp\left(\frac{qE_{gap}}{AK}\left(\frac{1}{T_r} - \frac{1}{T}\right)\right)$$

where T_r is the reference temperature of the photovoltaic cell; I_{rr} is the reverse saturation current at the critical temperature; and E_{gap} is the energy required to cross the band gap of the semiconductor material.

Under strong illumination, the photocurrent is much greater than $(V+IR_s)/R_{sh}$, so the output characteristic equation can be simplified to:

$$I = I_{ph} - I_o \exp\left(\frac{q(V + R_s I)}{AKT}\right)$$

Based on this mathematical model of photovoltaic cell output characteristics, this paper selects the Solarex MSX60 60W photovoltaic array [11] for modeling and builds the simulation model in MATLAB.

2.3 MPPT Control Circuit

The MPPT control circuit for photovoltaic systems incorporates a DC-DC converter [12], specifically a Boost circuit, to achieve maximum power point tracking. The Boost circuit schematic is shown in [Figure 3: see original paper]. The circuit consists of switch V, diode VD, energy storage inductor L, filter capacitor C, and load R. Under ideal conditions, both inductor L and capacitor C are sufficiently large.

The input-output voltage relationship of the Boost circuit is:

$$\frac{U_o}{U_i} = \frac{1}{1 - D}$$

where D is the duty cycle. The input resistance is:

$$R = \frac{U_i}{I_i} = (1 - D)^2 R_L$$

Thus, by adjusting the duty cycle D, the input resistance R of the Boost circuit can be modified. When R equals the equivalent internal resistance of the photovoltaic cell, the cell outputs maximum power [13]. Based on these formulas, a Boost circuit simulation model was built in MATLAB.

In the perturbation and observation method, the system can be observed and controlled by changing the duty cycle D of the Boost circuit in the DC-DC converter to track the maximum power point. Traditional step-size algorithms include fixed-step and variable-step adjustment methods. Fixed-step adjustment sets the step-size as a constant parameter to perturb the duty cycle for the next time step, causing the photovoltaic cell to operate at the maximum power point [14]. This algorithm makes step-size selection difficult and lacks control precision. Variable-step adjustment assigns different step-size values based on several stages of power change rate. It determines the output voltage adjustment direction according to current and previous power changes and adjusts the step size based on the magnitude of power variation, enabling faster tracking of the maximum power point [15].

3 Maximum Power Point Tracking Algorithm Based on Fuzzy Control and Adaptive Step Size Combination

3.1 Traditional Step-Size Algorithms

Traditional variable-step adjustment methods face the challenge of determining appropriate step-size values when adjusting the duty cycle D. If the adjustment value is too large, steady-state error increases; if too small, tracking time becomes longer, affecting dynamic response characteristics. To address this, this paper employs an optimized variable-step adjustment method by introducing a step-size adjustment parameter a that enables automatic step-size selection, improving both steady-state error and dynamic response [16].

The automatic adjuster is defined as:

$$a(k+1) = M\frac{\Delta P}{a(k)}$$

where $a(k)$ is the step-size adjustment value for duty cycle D, varying between 0 and 1; ΔP is the power variation; and M is a constant.

When external environmental factors change suddenly, conventional perturbation and observation methods might misinterpret output voltage or current changes as the cause of power variation, potentially adjusting the step size in a direction away from the maximum power point. Equation (8) resolves this issue. When $\Delta P/a(k)$ is small, it indicates that only duty cycle D changes determine output power P, so the next step-size adjustment $a(k+1)$ should not change significantly. When $\Delta P/a(k)$ is large, it means power variation is mainly caused by external factors like temperature and irradiance, requiring increased $a(k+1)$ to ensure rapid tracking to the maximum power point. When power fluctuations diminish, the adjuster recognizes that the system has reached the maximum power point and automatically reduces $a(k+1)$ to maintain stable output. This method exhibits strong adaptability and is therefore called the adaptive duty cycle step-size adjustment method [17].

3.3 Design of Fuzzy Controller Combined with Adaptive Step Size

Maximum power point tracking control typically involves detecting current output voltage and current values to determine the output power, which is then compared with the previous moment to judge the voltage adjustment direction [18]. This requires designing two control loop structures to measure two quantities. To reduce controller complexity, this paper adopts the method of adjusting duty cycle D to regulate system input-output relationships. To solve the step-size selection problem when adjusting D, the adaptive step-size adjustment method is employed with parameter a, enabling automatic step-size adjustment based on comparison of current and previous output power.

3.3.1 Selection of Input and Output Variables The fuzzy controller inputs are the power variation at time n, $E(n)$, and the duty cycle step-size adjustment value at time $n-1$, $A(n-1)$. The output is the duty cycle step-size adjustment value at time n, $A(n)$. The control principle is shown in [Figure 4: see original paper].

3.3.2 Determination of Input and Output Fuzzy Sets The power variation $E(n)$ is defined as 8 fuzzy sets: $E(n) = \{NB, NM, NS, NO, PO, PS, PM, PB\}$ with a range of $[-6, +6]$. The duty cycle step-size adjustment values $A(n)$ and $A(n-1)$ are defined as 6 fuzzy sets: $A(n) = \{NB, NM, NS, PS, PM, PB\}$ and $A(n-1) = \{NB, NM, NS, PS, PM, PB\}$, also with range $[-6, +6]$. Here, NB, NM, NS, NO, PO, PS, PM, PB represent negative big, negative medium, negative small, negative zero, positive zero, positive small, positive medium, and positive big, respectively.

3.3.3 Determination of Fuzzy Control Rules Combined with Adaptive Step Size The characteristic relationship between photovoltaic cell output power P and duty cycle D is nonlinear, similar to that between P and output voltage U [19]. The following rules are established:

1. If the current output power is increasing, the controller maintains the previous step-size adjustment direction; if decreasing, the step-size adjustment direction is reversed.
2. Far from the maximum power point, larger step-size values are used; near the maximum power point, smaller step sizes are applied.

Additionally, considering external condition effects: if environmental factors cause large changes in output power, the system automatically adjusts through the adaptive step-size method.

The general form of fuzzy control language rules is: IF "premise" THEN "conclusion" . For photovoltaic MPPT control, when power variation $E(n)$ is negative big (NB) and the previous step-size adjustment value $a(n-1)$ is also negative big (NB), it indicates decreasing output power far from the maximum power point. The duty cycle step-size adjustment should reverse direction with a large step size to accelerate tracking. Therefore, the current step-size adjustment value $a(n)$ should be positive big (PB). The linguistic rule is: IF power variation is NB AND previous step-size adjustment is NB, THEN current step-size adjustment is PB.

3.3.4 Establishment of Fuzzy Control Rule Table Based on the determined fuzzy control rules combined with adaptive step size, the fuzzy control rule table is established as shown in .

3.3.5 Determination of Membership Functions The membership functions for the MPPT controller are established using MATLAB' s Fuzzy Toolbox, with triangular shapes selected [20]. Since photovoltaic cell output power is asymmetric around the maximum point, the triangular shapes are also set as asymmetric. The membership functions for input and output variables are shown in [Figure 5: see original paper] through [Figure 7: see original paper].

4 Simulation and Analysis

4.1 Photovoltaic System Simulation Model

The photovoltaic system consists of three modules: PV module, MPPT module, and control circuit module. The simulation circuit diagram is shown in [Figure 8: see original paper]. The Transport Delay block implements a one sampling period delay. The PV module comprises a photovoltaic array of multiple cells, using the Solarex MSX60 60W array. Under standard test conditions (irradiance 1000 W/m², temperature 25°C), its basic parameters are listed in . Both PV and control circuit modules are built according to the formulas presented earlier. The load is 100Ω, with quantization factors $K_e = 0.01$ and $K_a = 200$. The MPPT control is implemented using a fuzzy logic controller.

To demonstrate the superiority of the adaptive step-size adjustment method, simulation models for fixed-step and traditional variable-step methods were also built under identical environmental conditions (irradiance 1000 W/m², ambient temperature 25°C) for comparison with the fuzzy-control-based adaptive step-size method. The simulation circuit diagram is shown in [Figure 9: see original paper].

4.2 Simulation Results Analysis

The output power simulation results for the fuzzy-control-based adaptive step-size algorithm are shown in [Figure 10: see original paper]. The results indicate that the system reaches maximum output power at 0.015 s, with a power value of approximately 1120 W. This demonstrates that the fuzzy controller enables rapid and smooth tracking to the maximum power point with minimal fluctuation.

A comparison of the three step-size algorithms is shown in [Figure 11: see original paper]. The fixed-step algorithm requires 0.15 s to achieve MPPT, while the traditional variable-step method needs 0.035 s—faster than the fixed-step approach. In contrast, the adaptive step-size adjustment method accomplishes MPPT control in only 0.015 s, significantly outperforming the other two algorithms while ensuring excellent system stability.

5 Conclusion

Photovoltaic power generation systems are highly nonlinear and difficult to describe with precise mathematical models. Therefore, employing fuzzy control for MPPT effectively compensates for the deficiencies of traditional control methods. This design uses an MPPT fuzzy controller to regulate the duty cycle of the boost circuit, adjusting the output power of the photovoltaic system.

The adaptive step-size adjustment method enables automatic step-size variation. To verify the optimization of this approach, three simulation models were built: fixed-step, traditional variable-step, and adaptive step-size methods. Under identical environmental conditions, the output waveforms were compared. Simulation results demonstrate that the adaptive step-size adjustment method significantly outperforms the other two algorithms. Consequently, the fuzzy-control-based adaptive step-size MPPT control enables photovoltaic systems to rapidly reach and maintain stable output at the maximum power point, ensuring optimal system operation.

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