

## Photovoltaic Cell Modeling and Variable Step Size MPPT Control Postprint

**Authors:** Ma Aihua, Li Lei, Shi He

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### Abstract

To address the issues of energy shortage and environmental pollution in the global context, a modeling methodology for photovoltaic (PV) cells—a common form of new energy—is proposed. Common maximum power point tracking (MPPT) algorithms for PV cells are analyzed, and based on this analysis, the perturb and observe method is improved, overcoming the limitations of the traditional perturb and observe method at various distances from the maximum power point. Using the Matlab/Simulink simulation platform, a mathematical model of the PV cell is established, and a control circuit is constructed based on the improved MPPT algorithm. The results demonstrate that the mathematical model can accurately simulate the operating characteristics of actual PV cells, the improved algorithm effectively compensates for the shortcomings of the traditional algorithm, and enables maximum power point tracking.

### Full Text

#### Preamble

**Ma Aihua, Li Lei, Shi He**

(School of Automation, Nanjing University of Science and Technology, Nanjing 210094, China)

**Ma Aihua**, female, born in 1991, master's degree candidate. Her research interests include power electronics applications in power systems.

**Li Lei**, male, born in 1975, Ph.D., associate professor, doctoral supervisor. His research interests include multilevel technology and power electronics applications in power systems.

## Abstract

In response to global energy shortages and environmental pollution, this paper proposes a modeling method for photovoltaic (PV) cells as a common new energy source. After analyzing typical PV cell MPPT algorithms, the perturbation and observation (P&O) method is improved to overcome the limitations of traditional P&O at various distances from the maximum power point. Using the Matlab/Simulink simulation platform, a mathematical model of PV cells is constructed, and a control circuit is built based on the improved MPPT algorithm. The results demonstrate that the mathematical model effectively simulates the operating characteristics of actual PV cells, while the improved algorithm successfully compensates for the deficiencies of traditional methods and achieves maximum power point tracking.

**Keywords:** Photovoltaic cell, disturbance observation method, variable step, Matlab/Simulink, maximum power point tracking

## 1 Introduction

Global energy shortages and environmental pollution have promoted the utilization of clean energy. Among various sources, solar energy has been widely adopted due to its advantages of local power generation and consumption, inexhaustible supply, pollution-free operation, low noise, and short construction cycles [1]. Currently, most manufacturers provide PV cell parameters measured under standard conditions (temperature of 25°C and irradiance of 1000 W/m<sup>2</sup>). However, in practical applications, external temperature and illumination conditions change continuously, necessitating the establishment of an accurate model to predict PV cell output. Furthermore, to maximize solar energy utilization, implementing Maximum Power Point Tracking (MPPT) is of great significance. MPPT is essentially a self-optimization process, with common methods including constant voltage tracking, incremental conductance, and perturbation and observation [2]. Among these, perturbation and observation (P&O) and incremental conductance (INC) are the most fundamental approaches [3], each with distinct advantages and disadvantages. The P&O method offers simple structure, requires few measured parameters, and is easy to implement, but its performance is significantly affected by the perturbation step size [4].

This paper introduces the most widely used mathematical model for PV cells and constructs a model based on relevant formulas. Building upon this foundation, the traditional P&O method is improved by employing a variable-step perturbation approach for MPPT control. Finally, simulations verify that the constructed PV cell module can effectively achieve output under real-time conditions, and the improved MPPT algorithm enhances MPPT performance.

## 2.1 Formula Derivation

PV cells are distributed power sources based on the photovoltaic effect, converting light energy into electrical energy [5]. The process involves two stages: first, photons (light waves) are converted into electrons, transforming light energy into electrical energy; second, a voltage is formed. [Figure 1: see original paper] shows the commonly used equivalent model of a PV cell.

As shown in [Figure 1: see original paper], a PV cell can be equivalent to three main components: a photocurrent source  $I_{ph}$ , a diode  $VD$ , and series and parallel resistances ( $R_{sh}$  and  $R_s$ ). The photocurrent  $I_{ph}$  is determined by the environmental light intensity, effective area of the PV cell, and stability.  $I_d$  is the dark current flowing through the diode PN junction without illumination. When a load  $R_L$  is connected, the output current value is  $I_L$ .

According to Kirchhoff's current law:

$$I_L = I_{ph} - I_d - I_{sh}$$

Generally,  $R_s$  is smaller than the diode forward resistance, so it can be assumed that  $I_{ph} = I_{sc}$  and  $I_d = I_o \exp\left(\frac{q(U_L + I_L R_s)}{AkT}\right)$ . Substituting into the equation yields:

$$I_L = I_{sc} - I_o \exp\left(\frac{q(U_L + I_L R_s)}{AkT}\right) - \frac{U_L + I_L R_s}{R_{sh}}$$

where  $I_{sc}$  is the short-circuit current of the PV cell,  $q$  is the electron charge ( $1.6 \times 10^{-19}$  C), and  $k$  is the Boltzmann constant ( $1.38 \times 10^{-23}$  J/K).

Equation (2) shows that PV cell output current is related to multiple factors, with output current and voltage coupled together, making calculations extremely complex. Moreover, several parameters are unknown and cannot be accurately measured, necessitating simplification while maintaining certain accuracy. Considering maximum power point tracking for PV cells, the output voltage  $U_m$  and current  $I_m$  corresponding to the maximum power point under specific temperature and illumination are introduced.

First, consider the open-circuit and maximum power point output of the PV cell.

### 2.1.1 Open-Circuit Condition

Under open-circuit conditions,  $I_L = 0$  and  $U_L = U_{oc}$ . Let  $C_1 I_{sc} = I_o$  and  $C_2 U_{oc} = \frac{AkT}{q}$ . Substituting into Equation (2) gives:

$$I_L = I_{sc} \left[ 1 - C_1 \exp\left(\frac{U_L}{C_2 U_{oc}}\right) \right]$$

### 2.1.2 At Maximum Power Point

When the PV cell operates at the maximum power point,  $U_L = U_m$  and  $I_L = I_m$ . Substituting into Equation (2) yields:

$$I_m = I_{sc} \left[ 1 - C_1 \exp\left(\frac{U_m}{C_2 U_{oc}}\right) \right]$$

Under normal conditions,  $\exp\left(\frac{U_m}{C_2 U_{oc}}\right) \gg 1$ , so the “-1” term in the parentheses of Equation (4) can be ignored. Applying the same treatment to Equation (3) and combining the two equations gives:

$$C_1 = \left(1 - \frac{I_m}{I_{sc}}\right) \exp\left(-\frac{U_m}{C_2 U_{oc}}\right)$$

Combining Equations (2), (5), and (6), the output current of the PV cell under specific conditions can be derived.

## 2.2 Engineering Mathematical Model

Generally, manufacturers only provide five parameters under standard test conditions: short-circuit current  $I_{sc}$ , open-circuit voltage  $U_{oc}$ , voltage  $U_m$  and current  $I_m$  at the maximum power point, and the corresponding power  $P_m$ . However, actual operating conditions differ from standard conditions, and according to PV operating characteristics, output current and voltage are not constant. Based on the derived formulas, various parameters under specific temperature and illumination conditions can be obtained. Typically:

$$\Delta I_{sc} = I_{sc} \cdot (1 + \alpha \Delta T) \cdot (1 + \beta \Delta S)$$

$$\Delta I_m = I_m \cdot (1 + \alpha \Delta T) \cdot (1 + \beta \Delta S)$$

$$\Delta U_{oc} = U_{oc} \cdot (1 - \gamma \Delta T) \ln(e + \delta \Delta S)$$

$$\Delta U_m = U_m \cdot (1 - \gamma \Delta T) \ln(e + \delta \Delta S)$$

where  $\alpha = 0.0025/^\circ\text{C}$ ,  $e$  is the natural logarithm base,  $\gamma = 0.00288/^\circ\text{C}$ ,  $\beta = 0.5$ , and  $\Delta T$  and  $\Delta S$  are the differences between specific conditions and standard conditions:

$$\Delta T = T - T_{nom}$$

$$\Delta S = \frac{S}{S_{nom}} - 1$$

where  $S_{nom}$  is the irradiance under standard test conditions ( $1000 \text{ W/m}^2$ ) and  $T_{nom}$  is the temperature under standard test conditions ( $25^\circ\text{C}$ ).

### 3.1 Traditional Perturbation and Observation Method and Its Drawbacks

The perturbation and observation method, also known as the hill-climbing method, includes voltage-type and current-type variants, with voltage-type being more common. According to the PV cell output P-V curve shown in [Figure 2: see original paper], there exists a voltage value  $U_m$  that maximizes output power. When using the perturbation and observation method, a perturbation  $\Delta U$  is applied to the voltage, and the PV cell output power  $P$  is calculated. If the output power increases, the perturbation direction is correct; otherwise, the direction is reversed.

The perturbation and observation method features simple structure, requires few measured parameters, and is easy to implement. However, traditional methods employ fixed step sizes and are significantly affected by the perturbation step size. When the perturbation step is too large, oscillations are likely to occur; when the step is too small, tracking speed becomes slow, making it unable to adapt to rapidly changing environments.

### 3.2 Variable-Step Perturbation and Observation Method

Under constant environmental conditions, the power characteristic curve of a PV cell is a single-peak function with a maximum point  $P_{max}$ . In traditional fixed-step perturbation and observation methods, the voltage increment is constant  $\Delta U$ , i.e.,  $U_{k+1} = U_k \pm \Delta U$ . As shown in [Figure 2: see original paper], with a fixed perturbation step, tracking speed is relatively fast when far from the maximum power point, but power fluctuations are significant when approaching the maximum power point [4]. If a long step can be used when far from the MPP and a short step when approaching the MPP, both convergence speed and stability at the maximum power point can be ensured. Here, a variable step factor  $\alpha$  is introduced to adjust the step size during perturbation.  $\alpha$  is related to the distance from the maximum power point—the farther the distance, the larger the value—ensuring convergence speed at both ends of the characteristic curve, i.e.,  $U_{k+1} = U_k \pm \alpha \Delta U$ . The specific concept is illustrated in [Figure 3: see original paper].

As shown in [Figure 3: see original paper], the range of the variable step factor  $\alpha$  is 0 to 1. During the climbing process, the smaller the output voltage, the larger the  $\alpha$  value. Specifically, it is determined by the power difference  $\Delta P$  or voltage difference  $\Delta U$ . Taking power difference as an example,  $\alpha$  takes the value of the function  $1 - \exp(-|\Delta P|)$ . The specific control flow of the variable-step perturbation and observation method is shown in [Figure 4: see original paper].

As shown in [Figure 4: see original paper], the difference between the variable-step perturbation and observation method and the traditional method lies in the introduction of a variable step factor  $\alpha$ , whose value is related to the output power difference  $\Delta P$  before and after perturbation. By measuring the output

voltage and current, the output power  $P$  is calculated. Using the voltage and power from the previous operating point,  $dU$  and  $dP$  are calculated. The sign of  $dU \times dP$  determines the direction of continued perturbation.

## 4 Simulation Analysis and Results

Based on the MPPT control flowchart shown in [Figure 4: see original paper], the control circuit was built in Matlab/Simulink, as illustrated in [Figure 5: see original paper].

The PV cell output supplies power to the load through a Boost circuit. The entire PV module consists of three parts: the PV cell output circuit, the boost circuit, and the variable load circuit. The circuit parameters are:  $C_1 = 550\mu\text{F}$ ,  $C_2 = 3300\mu\text{F}$ ,  $L_1 = 5\text{mH}$ ,  $R_1 = 25\Omega$ ,  $R_2 = 100\Omega$ , with the PV cell rated power at 5.6 kW. The bus voltage (load voltage) is set to 380 V, with a  $25\Omega$  load connected at the output side. At 0.3 s, a  $100\Omega$  resistor is connected in parallel; at 0.4 s, the ambient temperature changes from  $25^\circ\text{C}$  to  $15^\circ\text{C}$ ; at 0.5 s, the external light intensity changes from  $1000\text{ W/m}^2$  to  $600\text{ W/m}^2$ . The PV cell output voltage, current, and power are shown in [Figure 6: see original paper].

As can be seen from [Figure 6: see original paper], when temperature and illumination remain constant, power remains almost unchanged at the maximum power point even with load variations. After temperature decreases, power is reduced accordingly. When light intensity decreases, power is significantly reduced. However, after temperature and illumination changes occur, power, current, and voltage all quickly reach constant values.

Changing temperature and illumination conditions separately yields the output waveforms shown in [Figure 7: see original paper]. As shown in [Figure 7: see original paper], changes in light intensity have a greater impact on PV cell output than temperature changes.

## 5 Conclusion

This paper derives the output current expression for PV cells based on their equivalent circuit and provides calculation formulas for main parameters under specific temperature and illumination conditions. For MPPT control of PV cells, the limitations of traditional perturbation and observation methods are analyzed, and an improvement is proposed by introducing a variable step factor  $\alpha$ . This ensures both convergence speed when far from the maximum power point and stability near the maximum power point. Simulation results demonstrate that the established model and proposed improvement are reasonable and can be applied to other PV power generation systems.

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