Matlab/Simulink-Based Research on Maximum Power Point Tracking of Photovoltaic Generation

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Abstract

In order to improve the output efficiency of PV system, a novel variable step size perturbation and observation (P&O) method is proposed to track the maximum power point of PV system. Based on the mathematical model of PV system, this method tracks the maximum power point by regulating the output voltage after measuring the changes of output power. The simulation model of PV system is established, and the experiment is implemented. The experimental results show that the method can track the maximum power point fast and exactly, which shows that adaptive P&O has better steady-state and dynamic performance than the traditional P&O, and can improve the efficiency of photovoltaic power generation system effectively.

Keywords: solar energy; photovoltaic power generation; maximum power point tracking; perturbation and observation method; simulation analysis

1. Introduction

The rapid development of modern social economy causes energy and environment crisis, which requires us to reduce the dependence on traditional energy and improve the level of development and utilization of the renewable energy resources gradually. With the features of non-polluting and large reserves (can be said inexhaustible) [1-2], PV has become an important solution for society to break the energy and environment crisis, which is the development trend of future energy use.

Due to various external conditions (light intensity, temperature and load characteristics) and their influence factors, the output characteristics of photovoltaic power generation are apparent non-linear. In certain light intensity and environmental temperature conditions, the PV cell output power changes with voltage and appears like a single convex curve. Photovoltaic cells export maximum power only when they...
work at the vertex in the curve, which is known as the maximum power point. As the maximum power point changes with light intensity and temperature, the key of improving the overall efficiency of photovoltaic power system is real-time adjustment of photovoltaic cells operating point in the vicinity of the maximum power point, which is called maximum power point tracking (Maximum Power Point Tracking, MPPT) [3-5].

2. The Output Characteristics of Photovoltaic Cells

The output power of PV is the nonlinear function of ambient temperature and light intensity, the relationship between the output power and the temperature, light intensity is shown below. Figure 1 shows the output characteristic curve of photovoltaic cells at different temperature. From Figure 1 we can see that as the ambient temperature rises, the output power of photovoltaic cells decreases with the other conditions unchanged. As can be seen from Figure 2, other things being unchanged, the output power of photovoltaic cells increases as the light intensity strengthens. At particular light intensity, there is a unique maximum output power Pm for photovoltaic cell, which is called maximum power point.

The above analysis shows that the output power of photovoltaic cells, with considerable uncertainty, changes with the ambient temperature and light intensity. To this end, PV arrays must adopt maximum power point tracking control under different environmental conditions to achieve maximum power output.

![Figure 1. Output characteristics of photovoltaic cells at different temperature: (a) U-I curve at different temperatures; (b) P-U curve at different temperatures](image1)

![Figure 2. Output characteristics of photovoltaic cells under different light intensity: (a) U-I curve under different light intensity; (b) P-U curve under different light intensity](image2)

3. Two Common Methods of Maximum Power Point Tracking

3.1 Incremental Conductance Method

Incremental conductance method [6-7] (called IncCond for short) is one of the common used MPPT control algorithms. Incremental conductance method could estimate the relationship between the operating point voltage and the maximum power point voltage [8]. Think of the current I as a function of operating voltage U. For the formula of output power $P = U \cdot I$, we can obtain $dP/dU = I + U \cdot dI/dU$ by derivative at
both ends of the formula. We can see from the output characteristics of photovoltaic cells that when \(dP/dU > 0\), \(U\) is less than the maximum power point voltage \(U_{\text{max}}\); when \(dP/dU < 0\), \(U\) is larger than the maximum power point voltage \(U_{\text{max}}\); when \(dP/dU = 0\), \(U\) equals the maximum power point voltage \(U_{\text{max}}\). That is the following formula:

- if \(dI/dU > -1/U\), thus \(U < U_{\text{max}}\);
- if \(dI/dU < -1/U\), thus \(U > U_{\text{max}}\);
- if \(dI/dU = -1/U\), thus \(U = U_{\text{max}}\);

In this way, we can judge and adjust the operating point voltage \(U\) through the relationship between \(dI/dU\) and \(-1/U\) to realize maximum power point tracking. \(U_{\text{ref}}\) is the reference voltage, the flow chart of incremental conductance method is as follows:

![Diagram](image)

Figure 3. Method of increasing conductivity flow chart

When light intensity and outside temperature change, the incremental conductance method could control the output voltage to track the maximum power point voltage smoothly and could also reduce oscillation phenomena near the maximum power point. However, this control algorithm is very complicated, and the setting of adjusting voltage \(\Delta U\) influences the maximum power point tracking accuracy greatly. If \(\Delta U\) is too large, the tracking accuracy is not enough, the operating point can not reach the maximum power point all along. If \(\Delta U\) is too small, the tracking speed will slow down, the efficiency of photovoltaic power generation will also decrease.

3.2 Perturbation and Observation, P&O

Perturbation and observation method [9] (Perturbation and Observation, P & O), is also known as hill climbing method (Hill Climbing, HC). Its working principle is making a small active voltage perturbation in a certain working voltage of photovoltaic cells and observing the change direction of output power. If the output power increases then perturbation in the same direction should be kept, otherwise perturbation against the original direction should be made. The tracking diagram of perturbation and observation method is as follows:

![Diagram](image)

Figure 4. Tracking schematic diagram of the perturbation and observation method
Disturbance observation has been widely used in photovoltaic maximum power point tracking because of its simple control structure, few parameters, and easy implementation. However, due to its fixed step, the oscillation phenomenon occurs near the maximum power point, which reduces the power generation efficiency. Reducing the magnitude of each adjustment can weaken to a certain extent the oscillation near maximum power point, but the tracking to changes in the external environment will slow down, which also reduces the power efficiency. Therefore, selecting the appropriate step is the key for perturbation and observation method to achieve the desired effect.

4. Variable Perturbation Observation

The perturbation and observation method with fixed step reduces the effect of tracking significantly. The perturbation and observation method with variable step is adopted in this paper; the duty cycle of voltage regulation circuit serves as the control parameter on the maximum power point tracking. The control system uses duty cycle as the control parameter, which only needs one control loop and reduces the controller design difficulty. The relationship between PV output power $P$ with duty cycle $D$ is shown as below [10]:

$$P = P(K) = P(K-1) + \Delta P$$

The essence of disturbance observation method with variable step: far from the maximum power point, select a large step in order to approach the system optimal working state quickly; in the vicinity of maximum power point, select a small step to decrease or avoid system oscillation. The $P$-$D$ curve of the photovoltaic cells indicates that the absolute value of the derivative power to duty cycle gradually decreases close to the maximum power point. Therefore, we can construct a real-time step by the following formula:

$$\lambda(K+1) = \varepsilon |\Delta P|/\lambda(K)$$  \hspace{1cm} (1)

In the formula, $\lambda(K+1)$ $0 < \lambda(K) \leq 1$ is the adjustment step of duty cycle $D$, $\Delta P = P(K) - P(K-1)$ represents the magnitude of power change, $\varepsilon$ is the scale factor.

It can be seen from Equation (1) that, the adjustment step is small when the power change is small, which can guarantee the smoothness of output power; the adjustment step is large when the power change is large, which enables the system to track the maximum power point quickly and possess certain adaptive ability. The scale factor is proportional to the system sensitivity. The greater the value of the scale factor is, the more sensitive the system response [11]. The value of the scale factor should be based on the actual control requirement and system characteristics in application.

Based on the above analysis, the flow chart of the disturbance observation with variable step is obtained, and it’s shown in Figure 6. First, detect the output voltage and current of PV cells, calculate the current moment output power $P(K)$, and then get $\Delta P = P(K) - P(K-1)$. $\theta$ is the system threshold which determines the control accuracy of the controller. When $|\Delta P| < \theta$, the system works at maximum power region, it is unnecessary to adjust the duty cycle $D$ under this condition, otherwise the current operating point is far from the maximum power point, it is necessary to calculate a new step and then adjust the output power of photovoltaic cells. Next, judge the symbol of $\Delta P$, if it is greater than 0, then continue
perturbing in the original direction; otherwise perturb in the opposite direction shall be taken. The variable quantity flag, take 1 or -1, is the sign bit of the step, which decide the direction of the duty cycle perturbation.

![Flow chart](image)

Figure 6. Variable step disturbance observation flow chart

5. The analysis of Simulation

5.1 The equivalent model of photovoltaic cells

Siemens SP75 photovoltaic battery module is chosen in this paper for analysis, the simplified equivalent circuit of photovoltaic cells is shown below:

![Circuit diagram](image)

Figure 7. Simplified equivalent circuit of PV cells

The output characteristics of photovoltaic cells meet:

\[ I = I_{ph} - I_o \cdot \left\{ \exp\left[ \frac{q(U + IRs)}{36AkT} \right] - 1 \right\} \]  \hspace{1cm} (2)
The meaning of the symbols in the formula is shown in Table 1:

| symbols | meaning                                           | unit | value     |
|---------|--------------------------------------------------|------|-----------|
| \( I \) | Photovoltaic battery output current              | \( A \) |           |
| \( U \) | Photovoltaic battery output voltage              | \( V \) |           |
| \( I_{ph} \) | Photo-generated current                         | \( A \) |           |
| \( I_o \) | Reverse saturated current                        | \( A \) |           |
| \( q \) | Unit charge quantity                             | \( C \) | \( 1.6 \times 10^{-19} \) |
| \( A \) | The ideal factor                                 |      |           |
| \( k \) | Boltzmann constant                               | \( J/K \) | \( 1.38 \times 10^{-23} \) |
| \( T \) | PV cells surface temperature                     | \( K \) |           |
| \( I_d \) | Diode knot current                               | \( A \) |           |
| \( R_s \) | the equivalent resistance of photovoltaic cells  | \( \Omega \) |           |
| \( T_r \) | Reference temperature                            | \( K \) |           |
| \( S \) | Light intensity                                  | \( W/m^2 \) |           |
| \( I_{SCR} \) | short-circuit current of photovoltaic battery in standard test condition | \( A \) |           |
| \( K_1 \) | Short-circuit current temperature coefficient    | \( A/K \) |           |

5.2 Simulation principle of Simulink

As can be seen from Figure 7, PV output voltage meets \( U = I \times R_l \), \( R_l \) is the equivalent load resistance. Adjusting duty cycle to change the output voltage and then achieve maximum power point tracking is equivalent to adjusting the equivalent load resistance \( R_l \) to realize load matching and then achieve the maximum power tracking. Among them, the relationship between the duty cycle, output voltage and the equivalent load resistance can be approximated as:

\[
R_l = R/D
\]

(7)

\[
U = I \times R_l = I \times R/D
\]

(8)

\( R \) is the fixed load resistance.

Based on the above model, combined with the parameters [12] of Siemens SP75 photovoltaic battery module measured under standard conditions, using Matlab/Simulink simulation tool [13-14], we get the general simulation model of photovoltaic cells with the input of temperature \( T \), light intensity \( S \), the fixed load resistance \( R \) and duty cycle \( D \). The model is shown below:
Using the above model, establish the simulation system for maximum power point tracking based on the duty cycle perturbation. The system structure is shown in Figure 9. MPPT control algorithm is realized by blocks built in Simulink, and two control systems based on fixed step and variable step disturbance are established for simulation.

Set the ambient temperature 25°C, the light intensity from 600 W/m² to 1000 W/m² at the time 5s, running time 10s. In the simulation process, particular attention should be given to the cooperation of the sample time, and the initial perturbation is generated by the combination of ‘Switch’ and mutation signal.

5.3 Simulation results and analysis

In simulation, set the step $\lambda = 0.01$ and $\lambda = 0.001$ respectively in the duty cycle perturbation algorithm based on fixed step, the simulation results are shown in Figure 10 and Figure 11. Set the initial step $\lambda = 0.01$, scale factor $\varepsilon = 1/2500$ in the duty cycle perturbation algorithm based on variable step, the simulation result is shown in Figure 12.
As can be obtained by Figure 10-12: as to the fixed step $\lambda = 0.01$, the system tracks faster, has better dynamic performance, however, greater oscillation occurs in the steady state, which weakens the system stability and reduces the average output power; as to the fixed step $\lambda = 0.001$, the system has smaller steady-state error and oscillation is unobvious, but it response slower to the external change, which also affects the full utilization of solar energy; as to the variable step, the system could not only track the environmental change more rapidly, but have smaller steady-state error and no oscillation. This shows that, for the duty cycle perturbation method based on fixed step, if the step is too large, the system has better dynamic performance, but worse static performance; otherwise, the system static performance is good but the dynamic performance is poor; the duty cycle perturbation method based on changed-step is able to overcome the shortcomings of the duty cycle perturbation method based on fixed-step, which makes the system have good dynamic and static performance.

6. Conclusions

This article first analyzes the output characteristics of photovoltaic modules and the traditional maximum power point tracking algorithm and then proposes a new MPPT algorithm—the duty cycle perturbation and observation method based on variable step. By using mathematical model of photovoltaic modules and, simulation model is built in Matlab/Simulink. The photovoltaic output characteristics are simulated under different light and temperature conditions by the simulation model. The simulation results show that: this algorithm can overcome the shortcomings of the duty cycle perturbation based on fixed-step, and it enables the system to track the maximum power point quickly, reduce the system's steady-state
error, and ensure its stability. It is an effective control method to overcome the nonlinear characteristics of photovoltaic modules and improve the efficiency of photovoltaic power generation system.

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