Control strategy of grid-connected photovoltaic generation system based on GMPPT method

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Abstract. There are multiple local maximum power points when photovoltaic (PV) array runs under partial shading condition (PSC). However, the traditional maximum power point tracking (MPPT) algorithm might be easily trapped in local maximum power points (MPPs) and cannot find the global maximum power point (GMPP). To solve such problem, a global maximum power point tracking method (GMPPT) is improved, combined with traditional MPPT method and particle swarm optimization (PSO) algorithm. Under different operating conditions of PV cells, different tracking algorithms are used. When the environment changes, the improved PSO algorithm is adopted to realize the global optimal search, and the variable step incremental conductance (INC) method is adopted to achieve MPPT in optimal local location. Based on the simulation model of the PV grid system built in Matlab/Simulink, comparative analysis of the tracking effect of MPPT by the proposed control algorithm and the traditional MPPT method under the uniform solar condition and PSC, validate the correctness, feasibility and effectiveness of the proposed control strategy.

1. Introduction

As the world energy crisis and environmental pollution are becoming more and more serious, it is also of more significant importance to integrate more solar power. Grid-connected photovoltaic (PV) system makes it possible to the large-scale use of solar energy, and therefore becomes the hot topic. Maximum power point tracking (MPPT) control and grid-connected inverter control are the key control technologies of PV power generation systems. The cost of PV system is generally high, and hence it is necessary to make full use of PV maximum power efficiency. This makes the MPPT technology become indispensable for PV power generation control system control strategy [1-3]. In practice, due to complex operating conditions, such as partial shading condition (PSC), multiple local maximum power points (MPPs) can be exhibited on the power-voltage characteristic curve of the PV arrays [4-5].

Traditional direct MPPT control methods based on sampling data [6], such as perturbation and observation (P&O) method, incremental conductance (INC) method etc., have a good effect of maximum power point tracking under uniform solar irradiance condition [7-8]. However, such methods often fail and are prone to getting into local extreme point under shading conditions [9-11]. PV arrays actually working in a bad state can cause power seriously mismatch, energy loss, and even
damage of the PV modules. Thus, it is necessary to detect this problem and avoid it, which requires further research on global maximum power point tracking (GMPPT) method.

To solve this problem, many kinds of MPPT algorithms have been proposed in current literatures, such as improved direct GMPPT control method based on sampling data [12]. The entire search process can be divided into 2 stages: the first stage narrows the search range by moving working point; the second stage traces global maximum power point (GMPP) in a small area by traditional MPPT method. This method can track GMPP effectively under PSC [13] and judge the PSC without adding additional circuits. Literature [14] moves the working point according to the reference voltage provided for INC method by neural network algorithm trained under PSC. This keeps the INC method from getting into the local maximum power point (LMPP) under the PSC. In [15], through comprehensive study of the characteristic curves of the arrays under the PSC, it is concluded that under the PSC the voltages corresponding to the array power peaks are regular and predictable. MPPT can use the modified variable step size P&O method.

Another kind of method is the intelligent GMPPT control method based on the modern control theory. Swarm intelligence optimization algorithm (SIOA) is a probabilistic search algorithm, which includes Particle Swarm Optimization (PSO) algorithms, Ant Colony optimization (ACO) algorithm, etc. The application of PSO and ACO algorithms in PV MPPT control is respectively presented in [16-18] and [19-21], which reflects the MPPT algorithm based on swarm intelligence optimization effectiveness and feasibility. Though, these intelligent algorithms have very good effect on GMPPT, there are also some disadvantages. The neural network algorithm requires enough training data, which is usually not available; the fuzzy rules of fuzzy logic is not easy to be set; the convergence of PSO is easily affected by particle initial value; certain energy loss occurs due to too long tracking time.

Based on the above researches, in view of the merits and demerits of the INC algorithm and PSO algorithm, an improved GMPPT control method is improved combined with INC method and PSO algorithm. This method is an improved PSO algorithm suitable for multiple peak power points tracking. The algorithm contains two tracking methods: global tracking and local tracking. Firstly, possible GMPPs are rapidly approximated in global tracking mode. Next, the approximate location of GMPP is determined by contrast. Finally, the MPP is precisely determined in local tracking mode. Global tracking is realized by using improved PSO. The remains of this paper are organized as follows. In Section 2, the PV cell array and its output characteristic analysis is presented. In Section 3, the principles of INC method and PSO method are introduced firstly; then, the principle of the improved GMPPT is described in detail. In Section 4, simulations and analysis of the control effect of the improved GMPPT is addressed. In Section 5, a brief conclusion for this paper is provided.

2. Photovoltaic cell array and its output characteristic analysis

2.1. Photovoltaic cell equivalent circuit model

![PV cell equivalent circuit model](image)

**Figure 1.** PV cell equivalent circuit model

PV cell equivalent circuit model is shown in Figure 1. The ideal model of PV cell can be represented as a photosensitive current source $I_{pv}$ in parallel with a diode D. The photons in the light are absorbed by the PV cell. If the photon energy is higher than the energy band of the battery material, electrons are excited into the conductive band. If an external load connected to the output terminals of PV cells,
it generates electricity. As shown in Figure 1, PV cells equivalent circuit consists of a series resistance \( R_s \) and a shunt resistance \( R_{sh} \) and one optical drive current source.

Since the material defects and the ohmic losses exist in the battery substrate materials, metal wires and contact points, these losses in the PV cell model must be included in the series resistance \( (R_s) \) and the shunt resistance \( (R_{sh}) \). \( R_s \) is a key parameter, because it limits the maximum power \( (P_{max}) \) and the short circuit current \( (I_{sc}) \) of PV cells. \( R_s \) is associated with the battery resistance on the metal contact, the ohmic loss on the anterior surface of the battery, impurity concentration and junction depth. In the ideal case, \( R_s \) is zero. The loss caused by leakage current on the surface and lattice imperfection along the edge of the battery is associated by \( R_{sh} \). In the ideal case, \( R_{sh} \) is infinite. Therefore, in general analysis, series resistance \( R_s \) and the shunt resistance \( R_{sh} \) can be ignored. An accurate modeling of the PV cell [1] reflects the PV cell output characteristics under different solar intensity and temperature. The mathematical expressions of the model are as follows:

\[
\begin{align*}
I &= I_s - I_0 \left( e^{(U_s + iR_s)/nkT} - 1 \right) \\
I_s &= I_{s(T)} \left[ 1 + k \left( T - T_0 \right) \right] \\
I_{s(T)} &= G \cdot I_{sc(T)} / G_{(nom)} \\
K &= \left( I_{sc(T)} - I_{sc(T_0)} \right) / \left( T_2 - T_1 \right) \\
I_0 &= I_{0(T)} \left[ \left( T/T_0 \right)^{n_q} \cdot e^{-qU_s/(nkT)} \right] \\
I_{0(T)} &= I_{sc(T)} / \left( e^{-qU_s/(nkT)} - 1 \right) \\
R_s &= dU/dI_{sc} - 1 / X_U \\
X_U &= I_{0(T)} \left[ (q/kT_s) \cdot e^{-qU_s/(nkT_s)} \right]
\end{align*}
\]

Where, \( I \) refers to solar cell output current; \( U \) refers to the output voltage; \( I_s \) refers to short circuit current; \( I_0 \) refers to the saturation current of the PV cells in absence of light; \( n \) refers to the diode curve factor; \( q \) refers to electron charge; \( k \) refers to the Boltzmann constant; \( G \) refers to the intensity of solar radiation; \( G_{(nom)} \) refers to the standard radiation intensity (usually 1000W/m\(^2\)); \( T_0 \) refers to standard test temperatures (typically 25°C); \( I_{sc(T)} \) refers to the short circuit current when the temperature is \( T_1 \) and the radiation intensity is the standard radiation intensity; \( I_{s(T)} \) refers to short circuit current when temperature is \( T_1 \) and the radiation intensity is \( G \); \( U_{oc} \) refers to the open circuit voltage; \( U_g \) refers to energy band (crystalline silicon \( U_g \) is 1.12 eV).

### 2.2. Multi-peak characteristic curve of PV array

In PV power generation systems, to improve the output efficiency, it is necessary to array PV cells in series or in parallel connection. Considering the hot spot effect, an antiparallel bypass diode is arrayed on both ends of PV cells to prevent the damage of PV cells. The introduction of the bypass diode makes the P-U curve of the PV array show multi-peak features under the PSC. In this paper, taking 4 x 1 PV array as the study object, which is shown in Figure 2, the simulation analysis of multi-peak characteristics of PV arrays is taken in Matlab/Simulink.

The parameters of the PV array are listed in Table 1. To analyse the multi-peak characteristic curves of PV cells in series connection, the solar intensities in different time periods are set in Table 2. The temperature is 25°C. The P-U characteristic curves of the PV array in different time periods are shown in Figure 3. Obviously, the more complex shadow condition is, the more local peaks are.
conventional methods are prone to be trapped in local MPP (local MPP), and the GMPP cannot be found.

Figure 2. Structure of the object PV arrays

Table 1. Simulation parameters of the PV array

| Simulation Parameters | Value | Simulation Parameters | Value |
|-----------------------|-------|-----------------------|-------|
| Open-circuit voltage  | $U_{oc}$ | 42.48V | Current in MPP $I_m$ | 4.048A |
| Short-circuit current | $I_{sc}$ | 4.58A | Reference temperature $T_{ref}$ | 25°C |
| Voltage in MPP        | $U_m$ | 35V | Reference solar intensity $R_{ref}$ | 1000W/m$^2$ |

Table 2. The solar intensities in different time periods

| Time(s) | PV1(W/m$^2$) | PV(W/m$^2$) | PV3(W/m$^2$) | PV4(W/m$^2$) |
|---------|--------------|-------------|--------------|--------------|
| 0-0.25  | 1000         | 1000        | 1000         | 1000         |
| 0.25-0.5| 1000         | 1000        | 800          | 600          |
| 0.5-0.75| 1000         | 800         | 600          | 400          |
| 0.75-1.0| 1000         | 800         | 600          | 400          |

Figure 3. P-U characteristic curves of the PV array in different time periods.

3. Improved GMPPT control method

3.1. INC method and PSO method

Traditional MPPT control methods mainly include constant voltage (CV) method, P&O method and INC method. The INC method is a precise optimization algorithm based on mathematical model. The basic principle of INC method is to determine the PV array output voltage change its direction through the judgment of the size of the instantaneous conductance value and conductance variation. Formula derivation of INC method is as follows.

$$ P = U \times I $$  \hspace{1cm} (2)

$$ \frac{dP}{dU} = \frac{d(U \times I)}{dU} = I + U \times \left( \frac{dI}{dU} \right) $$  \hspace{1cm} (3)
\[
\frac{dP}{dU} = 0 \iff I + U \times \left( \frac{dI}{dU} \right) = 0 \tag{4}
\]
\[
\frac{dP}{dU} > 0 \iff I + U \times \left( \frac{dI}{dU} \right) > 0 \Rightarrow U < U_m \tag{5}
\]

The output P-U characteristics of PV cells by INC method is shown in Figure 4. Figure 4 reveals the mathematical meaning of the application of the INC method.

![Figure 4. P-U characteristics of PV cells by INC method.](image)

P&O method cannot be stable at one point because it needs to determine whether the MPP is reached by constant disturbance. Mathematical model of the CV method is simple. However, since Um is the approximate calculation, a certain degree of amplification of error can be produced and thus the efficiency is reduced. The INC method is a top option because of its fast response and high control precision. However, during the software implementation, the demand in the choice of the step length value is higher. Otherwise it is difficult to exert its advantages of high tracking precision.

PSO algorithm is a swarm intelligence optimization algorithm, which is widely used in the application of PV MPPT, and the iterative formula is provided by Eq. (6) – (7).

\[
V_{id}^{k+1} = \omega V_{id}^k + c_1 r_1 \left( P_{id}^k - X_{id}^k \right) + c_2 r_2 \left( P_{gd}^k - X_{id}^k \right) \tag{6}
\]
\[
X_{id}^{k+1} = X_{id}^k + V_{id}^{k+1} \tag{7}
\]

Where, \( \omega \) is the inertia weight; \( K \) is the current iteration number; \( V_{id} \) is the velocity; \( c_1 \) and \( c_2 \) are constants, known as the acceleration factor; \( P_{id}^k \) is the optimal value for particle \( i \) at the moment; \( P_{gd}^k \) is the global optimal value at the moment; \( r_1 \) and \( r_2 \) are random numbers, which are distributed in the interval [0, 1]. To prevent blind searching, generally, the location \( X \) and the velocity \( V \) are limited in certain ranges \([-X_{\text{max}}, X_{\text{max}}]\) and \([-V_{\text{max}}, V_{\text{max}}]\), respectively.

3.2. Improved INC method and improved PSO method

In Eq. (6), the step length is random because of the randomness of parameter \( r_1 \) and \( r_2 \), which will lead to too much time cost and low precision. Thus it is necessary to remove parameter \( r_1 \) and \( r_2 \). An improved GMPPT algorithm is proposed by combining the INC method and PSO method to fully exert their merits, as described as follows.

Firstly, the particle number and the position are initialised. According to the literature [16], the first particle position \( U_1 \) is 0.78\( U_m \). The \( k \) th particle position \( U_k \) is \( U_i + (k - 1)U_m \). The particle number \( N \) is 4.

Secondly, the improved PSO algorithm is adopted to realize global searching for the optimal local location.

- Calculate the output power corresponding to the initial voltage, which is the initial maximum power \( P_{\text{best}} \) for each particle. Then the initial global maximum power \( G_{\text{best}} \) can be obtained;
Update the voltage for each particle according to Eq. (6)-(7). A comparison is made between the output power of the particle at this time and the current maximum power $P_{\text{best}i}$, and $P_{\text{best}i}$ is updated;

- A comparison is made between the maximum power of all of the particles at this time and the current maximum power $G_{\text{best}}$, and $G_{\text{best}}$ is updated;

- Repeat steps 2) and 3) until the maximum voltage difference does not exceed 0.5% $V_{oc}$ between the optimal locations and all other positions, and then the iteration stops.

The global searching ends with retaining $G_{\text{best}}$ and its corresponding voltage $U_{\text{best}}$.

Finally, after searching the optimal local location, the variable step INC method [22] is adopted to track the MPP in the optimal local location. $U_{\text{best}}$ is used as the initial voltage for INC method. The smaller $|dP/dU|$ is, the closer working point is to the MPP.

Actually, it is impossible to track the exact MPP. The practical way is to approach the exact MPP. Therefore, it is unreliable to judge whether MPP is reached or not by $|dP| = 0$. An additional parameter $\theta$ is set depending on the accuracy requirements. $|dP| < \theta$ represents the MPP has been reached. $|dP| < \theta$ can be approximately considered as $|dP| = 0$ and at the MPP. When $|dP| > \theta$ , if $dP/dU < 0$, the working point will be on the left side of the MPP and the step $\Delta t$ is $b \times |dP/dU|$. When $|dP| > \theta$ , if $dP/dU < 0$, the working point will be on the right side of the MPP and the step $\Delta t$ is $a \times |dP/dU|$. Parameters $b$ and $a$ are step proportionality coefficients on left and right sides of the MPP. From the P-U curve, the left side step should be larger than the right side one and $b > a$. Thus PV system can quickly converge to MPP, reducing power losses. When shadow occurs or solar intensity changes, the output power of the PV array also follows the change. Thus, it is necessary to restart the PSO algorithm, making the system working in a new MPP stably. Variation of power $\Delta P$ can be represented as shown below.

$$\Delta P = \left| \frac{P - P_i}{P_i} \right|$$

(8)

When the performance period exceeds 1 minute or $\Delta P \geq 0.1$, PSO algorithm will restart. The flow chart of the improved GMPPT algorithm is shown in Figure 5.

4. Control effect of improved GMPPT

The object PV array is shown in Figure 2 and the corresponding parameters are listed in Table 1. Under the uniform solar condition, the solar intensity is 1000W/m$^2$ and the environment temperature is...
25 °C. The P-U curve is a unimodal curve as shown in Figure 3. Simulations are taken by using the INC method and the improved PSO algorithm respectively and P-t curves are shown in Figure 6.

From Figure 6, it can be seen that under the uniform solar condition, the INC algorithm takes about 0.0973 s to find the MPP. There is power oscillation close to the MPP, and oscillation difference is about 10.8 W, causing a large amount of power loss. The PSO algorithm takes about 0.0912 s to find the MPP. There is power oscillation close to the MPP as well, but the oscillation difference is about 3.2 W. The energy loss is reduced.

Under the PSC, the solar intensity is variable, as shown in table 2. The environment temperature is 25 °C. The P-U curve is a multi-peak characteristic curve as shown in Figure 3. Simulations are taken by using the INC method and the improved PSO algorithm respectively and P-t curves are shown in Figure 7.

From Figure 7, it can be obtained that during the t1 time period, due to the uniform solar condition, both algorithms can track the MPP. In t2 time period, when t = 0.25 s, the solar intensity of PV4 changed to 800 W/m². The INC algorithm finds the MPP in 0.2575 s, which is approximately 438 W with a power oscillation difference about 10.8 W. However, since the theoretical GMPP is about 511 W, the INC method causes a large amount of power loss. The PSO algorithm find the MPP in 0.2525 s, which is much closer to the theoretical value and the power oscillation difference is about 1.5 W. Thus, the energy loss is reduced. In t3 time period, when t = 0.5 s, the solar intensity of PV4 changed to 600 W/m² and the solar intensity of PV3 changed to 800 W/m². The INC algorithm find the MPP in 0.5096 s, which is approximately 288 W with a power oscillation difference about 8.5 W. However, since the theoretical GMPP is about 378 W, the INC method causes a large amount of power loss. The PSO algorithm find the MPP in 0.504 s, which is much closer to the theoretical value and the power oscillation difference is about 2 W. Thus, the energy loss is reduced. In t4 time period, when t = 0.75 s, the solar intensity of PV4, PV3, and PV2 are changed to 400, 600, and 800 W/m², respectively. The INC algorithm finds the MPP in 0.7585 s, which is approximately 158 W with a power oscillation difference about 6.3 W. However, since the theoretical GMPP is about 294 W, the INC method causes power loss. The PSO algorithm find the MPP in 0.7525 s, which is much closer to the theoretical value and the power oscillation difference is about 0.7 W. Thus, the energy loss is reduced.

Therefore, it can be concluded that the proposed method shows great advantages in convergence speed, tracking precision, power oscillation mitigation, and energy loss reduction.
5. Conclusions
An improved GMPPT method combined with INC method and PSO algorithm is proposed in order to solve the problem that traditional MPPT algorithm is easily trapped in local maximum power points under PSC, and to improve the convergence speed and tracking precision. Through experiment simulation and analysis, conclusions are as follows.
- Compared with the conventional INC method, the improved method can effectively avoid to be trapped in local MPPs and find the GMPP.
- The improved method can effectively improve the convergence speed and tracking precision, and the oscillations and energy loss are reduced.

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