Maximum Power Point Tracking of PV Systems Based On a Novel Adaptive Variable Step Size INC MPPT Method

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ABSTRACT: In the future solar energy will become a very important green energy. Maximum power point (MPP) tracking (MPPT) technology is widely used in solar photovoltaic (PV) systems to generate peak power for PV arrays that depend on solar irradiation and ambient temperature. Literature\cite{1} shows that the maximum power point tracking (MPPT) technology can improve the efficiency of photoelectric conversion by more than 20% and the economic cost is relatively low. Based on PROTUES, the output characteristics of PV arrays under different shadow conditions are simulated and the rule between local maximum power point and open circuit voltage is obtained. Among all the MPPT strategies, the incremental conductance (INC) algorithm and perturb and observe (P&O) algorithm are widely used due to the high tracking accuracy at steady state and easy implementation. In this paper, a novel adaptive variable step size INC MPPT method is proposed according to the above rule. This algorithm not only has the advantage of INC, but also can automatically adjust the step size to track the maximum power point of PV arrays. Compared with the adaptive perturb and observe (P&O) algorithm, the proposed approach can effectively improve the MPPT steady-state response speed and accuracy simultaneously. The theoretical analysis and design principle of the proposed algorithm are presented in this paper. The simulation results show that the algorithm can accurately track the maximum power point (MPP) with shadow. The average tracking time is only 0.13 seconds, and the power tracking efficiency reaches 98%.

1. INTRODUCTION
The core of MPPT technology is MPPT control algorithm. At present, many MPPT control algorithms have been proposed at home and abroad. Typical methods for tracking single peak maximum power point: Constant voltage tracking(CVT), Perturb & observe method(P&O), Incremental conductance(INC), Fuzzy control method and Neural network method and so on. MPPT control algorithm based on fuzzy logic realizes maximum power tracking\cite{2}. The optimal gradient algorithm is proposed to solve the problem of maximum power point tracking\cite{3}. Among all the MPPT strategies, the most common algorithms are P&O method and INC method. Incremental conductance method(INC), which is based on the fact that the slope of the PV arrays power versus voltage curve is zero at the MPP, has been proposed. To improve tracking accuracy and dynamic performance under different shadow conditions. In theory, when the derivative of the power and
voltage at the maximum power point is zero, the steady oscillation will disappear and better tracking effect can be obtained than the Perturb & observe method (P&O).

Under local shadow conditions, PV arrays power versus voltage curve will show multiple peaks, and the traditional MPPT algorithm is easy to fall into local maximum power point. In view of this problem, domestic and foreign scholars put forward two solutions: First, To compensate or optimize the structure of PV arrays under shadow conditions and the multi-peak optimization problem becomes single peak optimization problem[4][5]. Second, novel multi-peak optimization algorithm are proposed by studying the output characteristics of PV arrays under shadow conditions. The first solution, the topology of PV array is reconstructed to remove the bad influence of shadow[6][7], power compensation unit of the affected PV modules is connected in parallel to eliminate multiple extreme point characteristics[8][9]. This approach requires additional hardware circuits and the system cost is high and the control is complex. This approach has obvious flaws. In second solution, the global multi-peak maximum power point tracking can be realized by using the Novel algorithm without additional hardware. Literature [10] proposes a particle swarm algorithm to track the global peak point. Literature [11] proposes a neural network algorithm to track the global peak point. A two stage maximum power point tracking control is used for maximum power tracking[12]. However, this method can only be used for double peak PV arrays.

The traditional MPPT algorithm is seldom used to solve the tracking problem of multi-peak maximum power point. Based on Incremental conductance method (INC), a novel variable step size INC MPPT method are proposed in this paper. The algorithm can adjust the step size automatically according to the inherent PV arrays power versus voltage curve. If the operating point is far from MPP, it increases the step size which enables a fast tracking ability. If the operating point is near around the MPP, the step size becomes very small that the oscillation is well reduced contributing to a higher efficiency. This paper will give the theoretical analysis and design principle of a novel variable step size INC MPPT method. Both simulation and experimental design examples are provided, and the corresponding results confirm that the proposed method can effectively improve the dynamic performance and steady state performance simultaneously.

2. PV array output characteristics

When solar irradiation and atmospheric temperature are definite, PV cell is neither a constant-current source nor a constant-voltage source. In fact, it is a kind of nonlinear direct current source, which is not able to supply power arbitrarily. The equivalent circuit of PV cell is shown in Fig.1 and the equivalent mathematic model is described as:

\[
I = I_{ph} - I_o \left( e^{\frac{q(U+IR_s)}{nkT}} - 1 \right) - \frac{U+IR_s}{R_{ch}}
\]  

(1)

Where \( I_{ph} \) is the reverse saturation current of PN junction(in amperes); \( I_{ph} \) is the Photoproduction current that is proportional to solar irradiation(in amperes); \( I \) is the output current of PV array(in amperes), \( U \) is the output voltage of PV array(in volts); \( R_s \) is the series resistance(in ohms),and \( R_{ch} \) is the parallel resistance(in ohms); \( q \) is the electronic charge(in coulombs); \( I_o \left( e^{\frac{q(U+IR_s)}{nkT}} - 1 \right) \) is diode junction current; \( k \) is Boltzmann’s constant(in joules per Kelvin); \( T \) is the panel temperature(in Kelvin); \( A \) is the diode factor, When the thermodynamic temperature is \( T=300K \), \( A \approx 2.8; q=1.6\times10^{-19}C; k=1.38\times10^{-23}J/K \).
2.1 PV array output characteristics under different shadow conditions

This paper takes a 3×1 PV array as an example. As shown in Fig. 2, each PV cell (equivalent to a current source) is connected in parallel with a bypass diode. Explore the output characteristics of PV array under different shadow conditions. Under standard conditions (1000W/m², 25°C), different voltage controlled current source SUN were used to simulate situation of PV array under different shadows.

different voltage controlled current source SUN are shown in the following Table 1.

| Group | SUN1/v | SUN2/v | SUN3/v | Simulation Result(Fig.4) |
|-------|--------|--------|--------|--------------------------|
| 1     | 1      | 0.8    | 0.8    | P_1                      |
| 2     | 1      | 0.8    | 0.4    | P_2                      |
| 3     | 1      | 0.5    | 0.5    | P_3                      |
| 4     | 0.8    | 0.5    | 0.5    | P_4                      |
| 5     | 0.8    | 0.5    | 0.2    | P_5                      |

Figure 2 P-U characteristic curve of PV array with different voltage controlled current source SUN

Take group 5 as an example(P_5), there are three local maximum power points in P_5 (Fig.3). Open circuit voltage of PV array is \( U_{oc-array} = 10.5V \), the open circuit voltage of PV cell is \( U_{oc-module} = U_{oc-array} / 4 = 3.5V \), the three local maximum power point voltages are respectively \( U_{mpp1} = 1.98 = 0.75 \times U_{oc-module} \), \( U_{mpp2} = 5.22 = 2 \times 0.75 \times U_{oc-module} \), \( U_{mpp2} = 8.95 = 3 \times 0.75 \times U_{oc-module} \). The relationship between multi peak maximum power point and open circuit voltage under local shadow condition is obtained. For \( n \times m \) PV array, the maximum number of local maximum power points is \( n \).

The voltage corresponding to each local maximum power point is about \( k \times 0.75 \times U_{oc-module} \).
3. Maximum power point tracking algorithm

3.1 Adaptive variable step size INC MPPT algorithm

The step size of the traditional incremental conductance method is fixed. The larger step size can make the working point rapidly reach the maximum power point of the p-u characteristic curve. But it produces too much steady-state oscillations, resulting in lower efficiency. The smaller step size will reduce the tracking speed of the maximum power point. But it produces too much steady-state oscillations, resulting in lower efficiency. The smaller step size will reduce the tracking speed of the maximum power point. Thus, the MPPT with fixed step size should make a satisfactory tradeoff between the dynamics and oscillations. The flow chart of the adaptive variable step size INC MPPT algorithm is shown in Figure 3. Incremental iterative step size of the reference voltage is adaptive.

Where U(k) and I(k) are output voltage and output current of PV array sampling at time k. Incremental disturbances, whether acting on duty ratio or reference voltage, need to optimize the amplitude of disturbance step size. It is proposed that the amplitude of disturbance step size is directly dependent on the power derivative[13]. In this paper, a direct control formula for the amplitude of reference voltage step size is described as:

\[
\text{Step} = N \times \frac{dP}{dU} = N \times \frac{\Delta P}{\Delta U} = N \times \frac{P(k) - P(k-1)}{U(k) - U(k-1)}
\]

(2)

The step size will become tiny as \( \left| \frac{dP}{dU} \right| \) becomes very small around the MPP. In the formula, the coefficient N is the scale factor which is tuned at the design time to adjust the step size. Scaling factor N can seriously affect the tracking performance. If the parameters are simply adjusted manually, the process will be very tedious, and the results can only be applied to specific systems. According to literature [13], a simple formula to determine the scale factor N.

\[
N < \Delta U_{\text{max}} \times \left| \frac{dP}{dU} \right|_{\text{fixed step size}} / \Delta U_{\text{max}}
\]

(3)

where \( \Delta U_{\text{max}} \) is the maximum step-change in the reference voltage when designing the fixed step size INC MPPT algorithm. For the traditional fixed step size INC MPPT algorithm, the large step size is a good choice in the initial stage. The large step size disturbance is excellent in the initial dynamic tracking stage, but it cannot meet the requirements in the stable stage. It will produce steady state oscillations that cause additional power losses. In the startup phase, the adaptive variable step size INC MPPT algorithm is a fixed step size INC MPPT algorithm with the maximum step size, so as to rapidly approach the maximum power point and improve the optimization speed. Therefore, if (3) cannot be satisfied, the variable step size INC MPPT will be working with the maximum fixed step size and \( \Delta U_{\text{max}} \) is selected as the upper limit of adaptive variable step size.

According to 2.1, for nx1 PV array, the maximum number of local maximum power points is n. The voltage corresponding to each local maximum power point is about k \( \times 0.75 \times U_{oc \text{-module}} \). Therefore, in order to avoid missing the peak value of the maximum power point, the reference voltage in the algorithm can be set as k \( \times 0.75 \times U_{oc \text{-module}} \) (k=1, 2...n). The algorithm starts from the open circuit voltage to search for the maximum power point, so k can be evaluated from n. This can be completed by adding a simple constant voltage tracking (CVT) start program.

Following are the steps of the adaptive variable step size INC MPPT algorithm. As shown in the Table 2.

The adaptive variable step size INC MPPT algorithm and adaptive perturb and observe (P&O) algorithm both add small disturbances to the system. The tracking performance of the two algorithms will be compared in the following simulation experiments.

4. Simulation and experimental evaluation

In order to verify the performance of the proposed algorithm, the simulation model of PV system based on PROTPUES is shown in Figure 4. The control system is implemented in a pic16F877A and the PV Module’s parameters are chosen as follows:
Under the standard conditions (1000W/m², 25°C)

1) Maximum power: 17.9W
2) Maximum voltage: 8.51V
3) Open circuit voltage: 10.5V
4) Short circuit current: 4.30A

Table 2. adaptive variable step size INC MPPT algorithm:

| Step | Description |
|------|-------------|
| a.   | The initial reference voltage was set as \( U_{\text{ref}} = n \times 0.75 \times U_{\text{oc-module}} \) \( n_{i+1} = 0 \); \( P(k) = U(k)I(k) \); \( \Delta P = P(k) - P(k-1) \); \( \Delta U = U(k) - U(k-1) \); |
| b.   | Set the restart condition of the algorithm. When the shadow or light intensity changes dramatically, the output characteristics of the PV array also changes accordingly. The power change was set as \( |\Delta P| / P(k-1) \); When \( |\Delta P| / P(k-1) \) was greater than the threshold value \( \Delta P_{\text{tol}} \), the algorithm need to be restarted. |
| c.   | The maximum power point of \( nx1 \) PV array is tracked by the adaptive variable step size INC MPPT algorithm, and the maximum power and voltage are recorded. |
| d.   | Set the reference voltage as \( U_{\text{ref}} = k \times 0.75 \times U_{\text{oc-module}} \) \( k=1, 2 \ldots n \) If the power increase \( |\Delta P| \) is less than the threshold value \( k \), It is working at the local maximum power point. |
| e.   | The global maximum power point is obtained by comparing all local maximum power points |
The voltage of the voltage controlled current source SUN are respectively SUN1=1V, SUN2=0.5V and SUN3=0.8V. Simulation results are shown in Figure 5. The simulation result is a Three peak curve and the power value of the maximum power point is about 17.9W. The PV array tracking output power with adaptive perturb and observe (P&O) is 17.9 W and the tracking time is 403ms(Figure 6). The results indicate that adaptive perturb and observe (P&O) can accurately track the maximum power point and the tracking effect is excellent. However, the tracking speed is not fast enough and there are slight steady state oscillations. In this paper, an adaptive variable step size INC MPPT algorithm has been presented, which is able to improve the dynamic and steady state performance of the PV system simultaneously. The PV array tracking output power with adaptive variable step size INC MPPT is 17.9 W and the tracking time are 141ms(N = 0.01)(Figure 7). MPPT efficiency of the proposed algorithm is about 100%. Tracking time is reduced by 280% and steady-state oscillations are eliminated. It is evident that the PV system with adaptive variable step size INC MPPT has a better tracking performance.

Start waveforms with variable step size INC MPPT algorithm and initial reference voltage

$$U_{ref} = 0V$$

are shown in Figure 8. When the PV system approaches the maximum power point, the increment of step size becomes very small and eventually a smooth power curve is generated at the maximum power point. During the start-up phase, the step size of the power curve increases greatly. Limited by the performance of pic16F877A, PV system can not rapidly change the step size, resulting in large oscillations. This can be overcome by adding a simple constant voltage tracking (CVT) start program as shown in Figure 9. The preset voltage

$$U_{ref} = n \times 0.75 \times U_{oc\text{-module}} = 0.75 \times U_{oc\text{-array}}$$

to enable the PV system to rapidly approach MPP. Power curve is tracked to the maximum power point with fast speed and small step size, so the power curve is fast and smooth.

The adaptive variable step size INC MPPT algorithm, which has been suggested is able to make both the system very fast to reach the MPP and reduce the ripple around the MPP compared to the

Figure 3 The flow chart of the adaptive variable step size INC MPPT algorithm
conventional fixed step size INC MPPT algorithm. These achievements give an advantage to the proposed method.

Under standard test conditions, which are the temperature fixed at 25 °C and an irradiation fixed at 1000 W/m². The voltage of the voltage controlled current source SUN are respectively SUN1=0.8V, SUN2=0.8V and SUN3=0.8V. the maximum power of PV array is 24.1 W under standard test conditions (STC). The maximum power was obtained in the simulation by the proposed technique under the same STC is 23.9 W as shown in the Figure 10. So the tracking accuracy of the proposed method is almost 99.17%. Following the result of the Figure 11, it is noticed that conventional fixed step size INC MPPT algorithm. From these figures, the convergence time or response time towards the MPP of the variable step-size controller is faster than the conventional fixed step size INC MPPT algorithm. PV array with proposed algorithm gets to the MPP within 147.0ms while it takes 284ms for the fixed step size INC MPPT algorithm to track the MPP. The tracking time has been reduced by nearly 50%. On the other hand, the ripple amplitude of the proposed technique around the MPP is strongly reduced compared to the conventional fixed step size INC MPPT algorithm. After these interpretations it can be said that the proposed method responds sufficiently, promptly and effectively.

![Figure 4 PV system simulation model](image)

![Figure 5 P-U characteristic curve of PV array](image)

![Figure 6 PV array output power and PV voltage with adaptive perturb and observe (P&O)](image)
Figure 7  PV array output power and PV voltage with adaptive variable step size INC MPPT

Figure 8  Start waveforms with adaptive variable step size INC MPPT algorithm and initial reference voltage $U_{ref}=0V$

Figure 9  Start waveforms with adaptive variable step size INC MPPT algorithm and CVT start program.

Figure 10  PV array power curves with adaptive variable step size INC MPPT algorithm
5. CONCLUSION
In this paper, a novel adaptive variable step size INC MPPT algorithm is proposed, which can improve the dynamic and steady state performance of maximum power point tracking (MPPT). The theoretical analysis and design principle of the algorithm are proposed. In the PROTIUES simulation experiment, it can be clearly seen that the proposed algorithm has better tracking performance than the adaptive perturb and observe (P&O) algorithm and the fixed step size INC MPPT algorithm. Average MPPT efficiency of the proposed algorithm is about 90% and the average tracking time is only 0.14s.

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