Global MPPT algorithm with coordinated control of PSO and INC for rooftop PV array

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Published in The Journal of Engineering; Received on 6th October 2017; Accepted on 1st November 2017

Abstract: Considering the characteristics of rooftop photovoltaic (PV) array, a new mathematical model of PV array that is suitable for partial shading condition is built based on an engineering model of a solar cell. It is derived theoretically that output voltage of PV array can be expressed by piecewise function. Moreover, a global maximum power point tracking (MPPT) control method based on particle swarm optimisation (PSO) and incremental conductance algorithm (INC) coordination control is put forward under partial shading. When the environmental conditions are stable, MPPT can be achieved by INC control; otherwise, when the external conditions change, global maximum power point of PV systems can be located fast and accurately by PSO. So, the tracking efficiency is improved. Simulation results show that the PSO and INC coordination control methods have better tracking precision. It can be achieved easily and reduce hardware input costs. It also improves the PV array output efficiency.

1 Introduction

With the development of human society, the demand for energy is increasing day by day. Traditional energy sources pollute the environment and are not renewable. Otherwise, solar energy is clean, green and renewable. In recent years, China has vigorously promoted the rooftop photovoltaic (PV) programme, and solar power generation devices have been widely used. Maximum power point tracking (MPPT) control is the key technology of solar power generation, but the roof solar panels are easy to be affected by the surrounding buildings, trees and dust on the PV panels, which form the local shadow of the PV array. In this case, the $P-U$ curve of PV array will appear as multiple power peak points. Traditional methods such as hill-climbing method, perturbation and observation method and incremental conductance algorithm (INC) cannot distinguish the local extreme points and the global extreme point, so they are easy to fall into local extreme point [1–3]. To solve this problem, scholars put forward some global MPPT algorithm; particle swarm optimisation (PSO) algorithm is widely used. PSO is a new optimisation algorithm, which has good performance in multimodal function optimisation such as fast convergence, high precision, not easy to fall into a perturbation and observation method and incremental conductance algorithm (INC) cannot distinguish the local extreme points and the global extreme point, so they are easy to fall into local extreme point. However, the five parameters such as $I_s$, $I_{sc}$, $R_s$, $R_{sh}$, $A$, involved in (1), solar cells manufacturers do not provide them. Therefore, accurate modelling of solar cells is impossible. The solar cells engineering model uses only a few important technical parameters provided by the supplier such as $I_{sc}$, $U_{oc}$, $I_m$, $U_m$, $P_m$, expressed as [6]

$$ I = I_s[1 - C_1(e^{U/(C_2U_m)} - 1)] $$

(2)

where $C_1$ and $C_2$ denote

$$ C_1 = \left(1 - I_m/I_{sc}\right)e^{-U_{oc}/C_2U_m} $$

(3)

$$ C_2 = \left(U_m/U_{oc} - 1\right)\left[\ln(1 - I_m/I_{sc})\right]^{-1} $$

(4)

According to the characteristics of PV roof, based on the engineering mathematical model of a solar cell, A PV array model in partial shade is built, and the piecewise function expression of the output voltage of the PV array is obtained. At last, the paper put forward the coordination control algorithm of PSO and INC in partial shade. While the environment condition is stable, the INC algorithm is used to realise MPPT, and when the external condition is changing, PSO algorithm is used to locate the MPPT point fast and accurate, so as to improve the tracking efficiency.
Generally, the range of sunshine intensity $S$ on the ground is $0–1000$ W/m$^2$, and the temperature of solar cells varies greatly, possibly from 10 to 70°C. The parameters of $I_{oc}$, $U_{oc}$, $I_{m}$, $U_{m}$ will vary with the sunshine intensity and temperature. Depending on $T_{ref}$ and $S_{ref}$ of $I_{oc}$, $U_{oc}$, $I_{m}$, $U_{m}$, we can calculate $I_{oc1}$, $U_{oc1}$, $I_{m1}$, $U_{m1}$ with new sunshine intensity $S$ and temperature $T$, and then new $I$-$U$ curve will be obtained

$$\Delta T = T - T_{ref} \quad (5)$$

$$\Delta S = \frac{S}{S_{ref}} - 1 \quad (6)$$

$$I_{oc1} = I_{oc} \frac{S}{S_{ref}} (1 + \alpha \Delta T) \quad (7)$$

$$U_{oc1} = V_{oc}(1 - c \Delta T) \ln(1 + b \Delta S) \quad (8)$$

$$I_{m1} = I_{m} \frac{S}{S_{ref}} (1 + \alpha \Delta T) \quad (9)$$

$$U_{m1} = U_{m}(1 - c \Delta T) \ln(1 + b \Delta S) \quad (10)$$

where $S$ and $T$ denote new sunshine intensity and temperature, $T_{ref} = 25$°C, $S_{ref} = 1000$ W/m$^2$, $a = 0.0025$°C$^{-1}$, $b = 0.5$, and $c = 0.00288$°C$^{-1}$.

### 3 Output characteristics of PV array in partial shade

#### 3.1 Model of PV array

PV array is composed of several PV modules according to the load capacity, which has large power through series and parallel ways. Therefore, there is the following relationship between PV array and single PV module [9]:

$$U = N_s U_s \quad (11)$$

$$I = N_p I_p \quad (12)$$

$$P = N_s N_p \quad (13)$$

where $U_s$, $I_s$, $P_s$ denote the output voltage, output current, and output power of single PV module; $N_s$, $N_p$ denote the number of solar panels in series and parallel. If $N_s$ is the solar panel total number of PV array, then $N_s = N_s N_p$; $U$, $I$, $P$ denote the output voltage, output current, and output power of PV array.

So, the mathematical model of PV array in the same light can be described by the following equation:

$$I = I_{sc} N_p \left[1 - C_1 \left(\exp\left(\frac{U}{N_s U_w} - 1\right) - 1\right)\right] \quad (14)$$

When the PV array is working in the partial shade, the model is no longer adaptable. To establish the mathematical model for shade, this paper is based on the $4 \times 4$ array as an example, namely $N_s = 4$, $N_p = 1$, and the array structure is shown in Fig. 1. For each PV module in parallel with a bypass diode, it can prevent the PV module to work in reverse voltage. The array output is connected in series with a blocking diode, to prevent current from flowing into the PV array.

The equivalent circuit is shown in Fig. 2. Without considering the temperature difference, (1)–(7) shows that the value of $I_{oc1} - I_{oc4}$ is decided by respective sunlight intensity. If $S_1 > S_2 > S_3 > S_4$, then $I_{oc1} > I_{oc2} > I_{oc3} > I_{oc4}$. If $I_{oc1} > I_{oc4} < I_{oc3}$, the bypass diode of module 4 will be conducted, then the current which is more than $I_{oc4}$ will flow through the bypass diode and module 4 will have no current. In this case, only PV modules 1–3 have an external output power, while module 4 and its parallel bypass diode are loaded. The output voltage of each PV module is

$$u_1 = \ln\left(\left(\frac{i}{I_{oc1}} - 1\right)/(-C_{12})\right) + C_{13} U_{oc1} \quad (15)$$

$$u_2 = \ln\left(\left(\frac{i}{I_{oc2}} - 1\right)/(-C_{12})\right) + C_{12} U_{oc2} \quad (16)$$

$$u_3 = \ln\left(\left(\frac{i}{I_{oc3}} - 1\right)/(-C_{13})\right) + C_{23} U_{oc3} \quad (17)$$

$$u_4 = \ln\left(\left(\frac{i}{I_{oc4}} - 1\right)/(-C_{14})\right) + C_{24} U_{oc4} \quad (18)$$

$C_{11}$, $C_{12}$, $C_{13}$, $C_{14}$, respectively, denote $C_1$ of PV modules 1, 2, 3, 4 under different sunshine intensity and temperature; $C_{21}$, $C_{22}$, $C_{23}$, $C_{24}$, respectively, denote $C_2$ of PV modules 1, 2, 3, 4 under different sunshine intensity and temperature; $U_{oc1}$, $U_{oc2}$, $U_{oc3}$, $U_{oc4}$, respectively, denote $U_{oc}$ of PV modules 1–4 under different sunshine intensity and temperature; and $i$ denotes the output current.

Depending on the output current $i$, the total output voltage $u$ can be described by the following piecewise functions:

$$u = \begin{cases} 
  u_1, & i < I_{oc1} \\
  u_1 + u_2, & I_{oc1} < i < I_{oc2} \\
  u_1 + u_2 + u_3, & I_{oc2} < i < I_{oc3} \\
  i, & I_{oc3} \leq i \leq I_{oc4} 
\end{cases} \quad (19)$$

#### 3.2 Output characteristic curve of PV array

The above models are simulated by MATLAB/simulink, and two kinds of illumination situations are discussed:

(i) Illumination situation 1: $S_1 = S_2 = S_3 = S_4 = 1000$ W/m$^2$. Its $P$–$U$ curve as shown in Fig. 3, the maximum power $p = 1025$ W, at this time the output voltage is $124$ V, and there are one power extreme point.
4.1 PSO algorithm

PSO algorithm is an efficient method for global optimisation of many extreme functions [10]. Swarm intelligence is optimised through swarm cooperation and competition among groups, and then used to instruct search. In each iteration, the particle updates its position and velocity through two extreme points. The first is the optimal solution found by the particle itself until the present moment, referred to as \( P_{\text{best}} \), and the second is the optimal solution of the entire population, referred to as \( G_{\text{best}} \). At \( k+1 \) iteration, velocity \( v_{i}^{k+1} \) and position \( s_{i}^{k+1} \) of the \( i \) particle are updated as follows:

\[
v_{i}^{k+1} = w v_{i}^{k} + c_{1} r_{1} (P_{\text{best}} - s_{i}^{k}) + c_{2} r_{2} (G_{\text{best}} - s_{i}^{k}) \tag{20}
\]

\[
s_{i}^{k+1} = s_{i}^{k} + v_{i}^{k+1} \tag{21}
\]

where \( k \) denotes the number of iterations; \( w \) denotes the inertia weight; \( c_{1} \) and \( c_{2} \) denote the learning factors; \( c_{1} \) denotes the part of self-cognition; \( c_{2} \) denotes the social cognition part; \( r_{1} \) and \( r_{2} \) obey the uniform random numbers on \([0,1]\).

In this paper, the total output power \( p \) is chosen as the fitness function

\[
p = u \times i \tag{22}
\]

\( u \) is the piecewise function shown in the above (19).

4.2 Restart condition of PSO algorithm

When the shadow or radiation intensity changes, the output power of PV array also changes, so we need to restart the PSO algorithm to make the system work stably at the new maximum power point. The relative change of power \( \Delta p \) represents as follows:

\[
\Delta p = \frac{|P_{2} - P_{1}|}{P_{1}} \tag{23}
\]

where \( P_{1} \) and \( P_{2} \) are, respectively, the output power calculated from the previous and present moments of the PV array. Simulation results show that the relative change of power \( \Delta p \) is \( >0.1 \), when the shadow changes dramatically. So, the restart conditions for the mutation are \( \Delta p > 0.1 \).

4.3 Algorithm flow of coordinated control

The flowchart of the MPPT control algorithm coordinated by PSO and INC is shown in Fig. 5.

5 Simulation and analysis

To test the effectiveness of the MPPT control algorithm coordinated by PSO and INC, the simulation is analysed in this paper. The PV array is consisted of four 36 V/255 W PV modules. The MPPT control algorithm coordinated by PSO and INC is written based on arm 7.

The main circuit adopts buck circuit, and the PV array is composed of four 36 V/255 W PV modules. The MPPT control algorithm coordinated by PSO and INC is written based on arm 7.

The output voltage \( u \) of PV array is the sampling voltage, and also the input voltage of buck circuit, and \( u_{0} \) is the output voltage. The MPPT controller calculates the voltage of the global MPPT point with coordinated control algorithm, using (19). If the output voltage \( u \) of PV array is updated, the pulse generator generates a pulse-width modulation wave, and switch duty \( D \) will be changed, then \( u_{0} \) will be changed too. At last, the global MPPT will be achieved. The simulation parameters are as follows: boost

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inductor $L$ is 0.3 mH; $C_1$ of the bus side capacitance is 1.00 mF; filter capacitor $C_2$ is 1 mF; and the output load is 5 $\Omega$ resistor.

The parameters of the controller are set as follows:

(i) **PSO algorithm**: The number of particles is 20, the number of iterations is 15, the particle initialisation space is $5 - 14$, the maximum particle velocity is 0.13 of the search area, the inertia weight $W = 0.8$, and the learning factor $c_1 = c_2 = 1.4$.

(ii) **INC algorithm**: The sampling period is 0.0005 s, with variable step size, step $k_1 = 0.001\times\text{abs}(dp/du)$. Here, $dp/du$ denotes the first derivative of output power $p$ of PV array with respect to the output voltage $u$. To test the effectiveness of the multi-peak MPPT method proposed above, three cases are put forward as follows.

### 5.1 Analysis of PSO algorithm

The sunlight intensity of four PV modules is illumination situation 1: $S_1 = S_2 = S_3 = S_4 = 1000$ W/m$^2$, it becomes illumination situation 2 in 0.3 s because of partial shade, $S_1 = S_2 = 1000$ W/m$^2$, $S_3 = 500$ W/m$^2$ and $S_4 = 400$ W/m$^2$. In 0.6 s, it becomes illumination situation 1: $S_1 = S_2 = S_3 = S_4 = 1000$ W/m$^2$. PSO algorithm plays a main role. Table 1 shows the error between the theoretical and simulation values of PSO algorithm. The simulation waveform is shown in Fig. 7.

### 5.2 Analysis of INC algorithm

The sunlight intensity of four PV modules is: $S_1 = S_2 = S_3 = S_4 = 1000$ W/m$^2$, it becomes $S_1 = S_2 = 1000$ W/m$^2$, $S_3 = S_4 = 900$ W/m$^2$ while sunlight intensity changes in 0.2 s. The light intensity changes little, so the INC algorithm plays a main role. Table 2 shows the difference between the theoretical and simulation values of INC algorithm. The simulation waveform is shown in Fig. 8.

### 5.3 INC algorithm for multi-peak MPPT

The tracking waveform of INC algorithm under illumination situation 2 is shown in Fig. 9. The simulation result shows that the maximum output power of the INC algorithm is 450 W, close to the theoretical value of 448.8 W, which is the secondary maximum power according to Section 3.2 of illumination situation 2, so it is falling into the local extreme point.

### 6 Inclusion

According to the local shadow of the rooftop PV array, the piecewise function mathematical expression of the output voltage of the PV array is established. According to the characteristics of multiple extreme points in the output power, a coordinated control algorithm based on PSO and INC algorithms is proposed, and a simulation model with MATLAB/Simulink is built. The simulation results show that PSO plays a main role if the changes of light intensity are high. PSO can quickly locate the global maximum power point, and if the changes of light intensity are not obvious, the INC algorithm plays a main role. All the values are very close to the theoretical ones. In the case of multi-peak, compared with the INC algorithm separately, the simulation results show that the INC algorithm may fall into the local extreme point. The coordinated control algorithm of PSO and INC is simple, which will reduce the hardware cost and improve the efficiency of PV power generation.

### 7 Acknowledgments

This work was supported by the National Natural Science Foundation of China (61422201), the science project foundation...
of Guangdong Provincial Education Department (2015KQNCX208), and science and technology plan project foundation of Zhongshan City (2015B2309, 2016B2156).

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