

Analysis of Output Characteristics of Photovoltaic Array under Time-varying Shadow

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Abstract. The Photovoltaic (PV) array is often obscured by moving clouds, surrounding buildings, and so on. That results in the formation of partial shadow in the PV array, which leads to the multi-peak characteristics of the PV array to make the traditional maximum power point tracking (MPPT) method invalid. Therefore, it is necessary to explore and analyze the output characteristics of the PV array under partial shadows in order to improve the effectiveness and accuracy of MPPT. Partial shadow is divided into static shadow and time-varying shadow. In this paper, the output characteristics of the PV array under time-varying shadow are mainly studied. The motion of the extreme points during the process of shadow variation is obtained. These research results lay the foundation for the following MPPT algorithm.

1.Introduction

Solar power generation is a new energy development field with the most widely application and the fastest development speed. Under different illumination and temperature conditions, there is such a point that the output power of the PV array is maximum at this point, and the point is called the maximum power point. In order to increase the conversion efficiency of the PV array, it is necessary to operate near the maximum power point. The PV array in the open air is often obscured by moving clouds, making the illumination uneven throughout the array and easily resulting partial shadows. Because the output of the PV array has obvious nonlinearity, which is affected by illumination, temperature and load ^[1]. When the weather changes, the U-I curve of the PV array changes with the change of illumination. Similarly, the output power curve of the PV array will also change with it, resulting in the fluctuation of the maximum power point. Therefore, the partial shadow will lead to multiple local maximum power points in the PV array, and resulting in power loss that reaches more than 70% of the output power of the whole PV array ^[2]. It is necessary to analyze the output characteristics of the PV array under partial shadows in order to improve the effectiveness and accuracy of MPPT.

Many references focus on the static shadow in the study of partial shadow ^[3-4]. However, the shadow is always changing in practice, namely time-varying shadow. The characteristics of output curve and the distribution of local extremum of the PV array under time-varying shadow are analyzed deeply, which provides the basis for the research of MPPT algorithm.

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2. Modeling of PV array

In general, a solar cell can be simplified to a P-N junction. The P-N junction produces a constant photocurrent I_{ph} which does not change with the operating state of solar cell when it is illuminated by a constant light source, so it can be regarded as a constant current source [5]. Therefore, each solar cell can be equivalent to such circuit consisting a parallel circuit with a forward diode and a constant current source and two types of resistors, one of which is series resistor R_s and the other is parallel resistor R_{sh} , as shown in Fig.1.

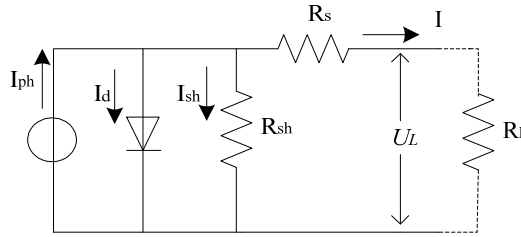


Figure 1. Equivalent circuit of solar cell

The current I_d flowing through diode P-N junction is: $I_d = I_0 (e^{\frac{qU_d}{AKT}} - 1)$ (1)

Where, I_0 is the reverse saturation current. K is Boltzmann constant, the value is $1.381 \times 10^{-23} J/K$. T is the absolute temperature on solar cell surface, °F. A is the ideal factor of diode, $1 \leq A \leq 2$. q is the magnitude of charge, the value is $1.602 \times 10^{-19} C$ [6].

U_L and I are the voltage and current of the load R_L , respectively. R_s is series resistance, and then the current I_{sh} flowing through the bypass resistance R_{sh} is:

$$I_{sh} = \frac{U_L + R_s I}{R_{sh}} \quad (2)$$

According to Kirchhoff's current law,

$$I = I_{ph} - I_d - I_{sh} \quad (3)$$

Where, I_{ph} is photocurrent of the solar cell, and then the output current expression of the solar cell is shown in equation (4):

$$I = I_{ph} - I_0 (e^{\frac{qU_d}{AKT}} - 1) - \frac{U_L + R_s I}{R_{sh}} \quad (4)$$

For the solar cell, it can be seen from equation (4) that the larger the parallel resistance R_{sh} , the smaller the series resistance R_s , the better its performance, and the larger the output current. In practice, the value of series resistance R_s is generally less than 1Ω , while the parallel resistance R_{sh} is generally several thousand ohms. Since R_s is much smaller than R_{sh} , the equation (4) can be simplified as:

$$I = I_{ph} - I_0 (e^{\frac{qU_d}{AKT}} - 1) \quad (5)$$

At the same time, according to Kirchhoff's voltage law, the relationship between the voltage of the diode U_d and the voltage of the load U_L is as follows:

$$U_d = U_L + IR_s \quad (6)$$

So it can be approximated as $U_d = U_L$ and $I_{sh} = I_{sc}$, where, I_{sc} is the short-circuit current. So equation (5) can be simplified as:

$$I = I_{sc} [1 - C_1 (e^{\frac{U_L}{C_2 U_{oc}}} - 1)] \quad (7)$$

$$C_1 = (1 - \frac{I_m}{I_{sc}}) e^{\frac{-U_m}{C_2 U_{oc}}} \quad (8)$$

$$C_2 = (\frac{U_m}{U_{oc}} - 1) / \ln(1 - \frac{I_m}{I_{sc}}) \quad (9)$$

Where, U_{oc} is the open-circuit voltage. C_1 and C_2 are the correction coefficient. U_m and I_m are the voltage and current corresponding to the maximum power point, respectively. U and I are the working voltage and current of the solar cell, respectively.

3. Influence of partial shadow on PV array

All modules of the PV array are subjected to forward voltage drop and output electric energy under uniform illumination condition. However, the PV array is shaded when the environment changes, the shaded modules of the PV array are no longer used as a power source, but as a load to consume the energy generated by other modules, and the shaded modules will generate heat. The PV modules will be permanently damaged when the heat reaches a certain level, which makes the whole PV array lose their effectiveness. This is called the hot spot effect.. Once it is more than the maximum power of a single PV cell, the heat generated by the PV cell will cause irreversible damage to the module. According to Kirchhoff's current law, if the output current of unoccluded PV module is more than the short-circuit current of shaded PV module, the shaded PV module is subjected to reverse voltage drop, which is regarded as the load consuming the output power of the other normal module in the form of heat. This leads to the reduction of the output power and the conversion efficiency of the PV array. At the same time, the whole PV array may eventually be damaged with the accumulation of heat.

4. Causes of multiple peaks

In order to solve the problem that partial shadow leads to the occurrence of hot spots, a solution using parallel bypass diode is adopted [7]. In addition, the battery will discharge to the PV array during the night and rainy weather, causing power reflow. In order to prevent such phenomenon, it is necessary to connect a diode, which performs unidirectional conduction, in series with PV array, such diode is called blocking diode. Due to the connection of the bypass diode and the blocking diode, the P-U characteristic curve of the PV array presents multiple peak points under partial shadow, which increases the difficulty of MPPT [8].

Taking a PV array composed of two modules with identical parameters in series as an example (as shown in Fig.2), the formation principle of multiple maximum power points under partial shadow is illustrated.

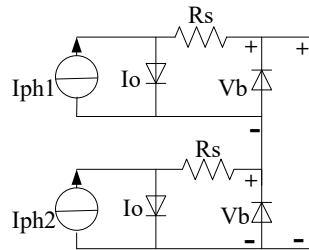


Figure 2. Equivalent circuit of PV modules in series

Since the parameters of the two modules are completely consistent, their working current I_{ph1} and I_{ph2} , working voltage U_1 and U_2 are all the same when the illumination is uniform, so the output power of the two modules is the same, and the P-U characteristic curve of the PV array has only one peak. However, if there is a shadow at module2, then $I_{ph1} < I_{ph2}$. Voltage polarity of module2 is reversed since the output current does not match. The diode connects to module 2 in parallel will be switched on when the value of reverse voltage U_2 is equal to break-over voltage U_d of the diode [9]. Then module2 is short-circuited and does not continue to output power. The output characteristic equation of the PV array is as follows:

$$U = \frac{AKT}{q} \ln\left(\frac{I_{ph1} - I}{I_0} + 1\right) - U_d - IR_s, I_{ph2} < I \leq I_{ph1} \quad (10)$$

When the working current I_{ph2} is continuously reduced, the voltage of module 2 becomes forward voltage until $I_{ph1} = I_{ph2}$, and the diode is turned off in reverse [10]. The output characteristic equation of the PV array is as follows:

$$U = U_1 + U_2 = \frac{AKT}{q} \ln\left(\frac{I_{ph1} - I}{I_0} + 1\right) + \frac{AKT}{q} \ln\left(\frac{I_{ph2} - I}{I_0} + 1\right) - 2IR_s, 0 \leq I \leq I_{ph1} \quad (11)$$

In summary, the output voltage of the series array can be represented by a piecewise function, namely:

$$U = \begin{cases} \frac{AKT}{q} \ln\left(\frac{I_{ph1}-I}{I_0}+1\right) - U_d - IR_s, & I_{ph2} < I \leq I_{ph1} \\ \frac{AKT}{q} \ln\left(\frac{I_{ph1}-I}{I_0}+1\right) + \frac{AKT}{q} \ln\left(\frac{I_{ph2}-I}{I_0}+1\right) - 2IR_s, & 0 \leq I \leq I_{ph1} \end{cases} \quad (12)$$

According to $P=UI$, the output power piecewise function is obtained as

$$P = \begin{cases} \frac{AKTI}{q} \ln\left(\frac{I_{ph1}-I}{I_0}+1\right) - U_d I - I^2 R_s, & I_{ph2} < I \leq I_{ph1} \\ \frac{AKTI}{q} \ln\left(\frac{I_{ph1}-I}{I_0}+1\right) + \frac{AKTI}{q} \ln\left(\frac{I_{ph2}-I}{I_0}+1\right) - 2I^2 R_s, & 0 \leq I \leq I_{ph1} \end{cases} \quad (13)$$

There are two maximum power points in the P-U characteristic curve of the PV array, which is in the case that the PV array consists of only two modules in series. Similarly, if the PV array is composed of a large number of modules in series and in parallel, there will appear multiple maximum power points in the P-U characteristic curve of the PV array if the PV array is shaded, which leads to difficulties in tracking global maximum power point.

5. Analysis of output characteristics of PV array under time-varying shadow

The PV array may be partially shaded by trees, buildings, or clouds. Among them, the floating clouds move with time, so it is necessary to study the output characteristics of the PV array under time-varying shadow [11].

In this paper, the PV array model with 5×5 is selected for simulation analysis, simulation models of PV modules is shown in Fig. 3. It is assumed that the light intensity is divided into three levels, that is, without shadow, half shadow and full shadow. The light intensity without shadow, for half shadow and for full shadow is defined as 1kW/m^2 , 0.5kW/m^2 and 0.1kW/m^2 , respectively [12]. As is known to all, the cloud movement is complex and changeable. For the convenience of studying, the cloud movement is divided into three kinds of moving modes, the first is that regular cloud passes through the PV array from left to right; the second is that regular cloud passes through the PV array from top to bottom; the third is that irregular clouds passes through the PV array from left to right, which is shown in Fig. 4.

The output characteristic curves of the PV array that is affected by different moving shadows are shown in Fig. 5 (a) - Fig. 7 (a). In order to better observe the effect of clouds passing through the PV array in different modes on the output characteristics of the PV array, the curves are converted into the surfaces, as shown in Fig. 5 (b) - Fig. 7(b).

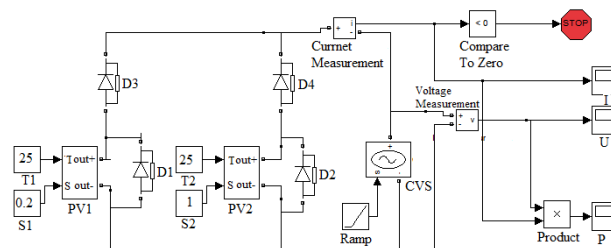


Figure 3. simulation models of PV modules

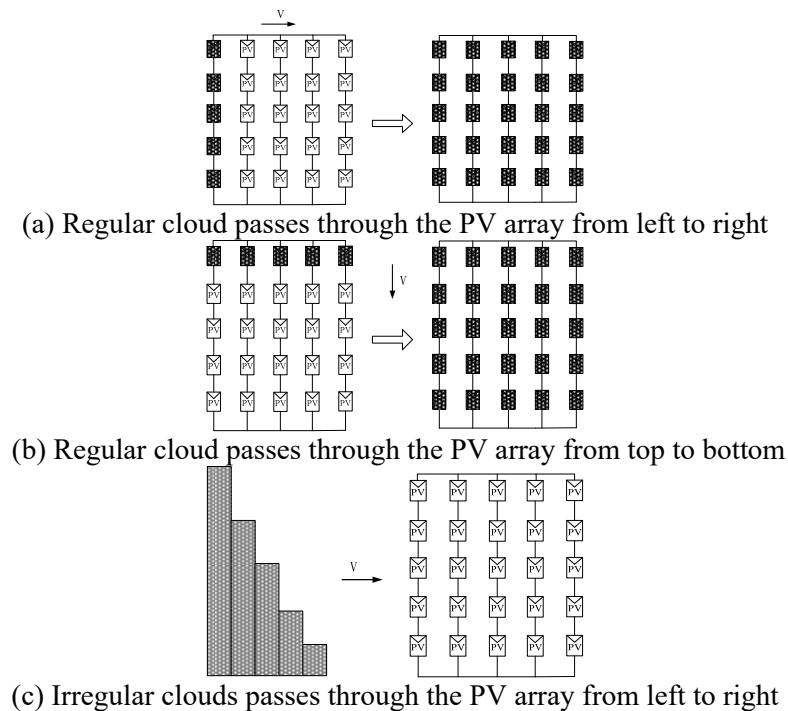
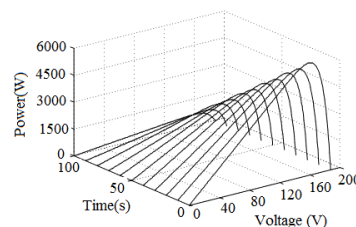


Figure 4. Schematic diagram of PV array with time-varying shadow

As can see from Fig. 5, when regular clouds pass through the PV array from left to right uniformly, there are not multiple extreme points in the P-U characteristic curves of the PV array. The open circuit voltage of the PV array decreases slightly, and the position of the voltage corresponding to the maximum power point little changes. However, the output power of the PV array changes greatly and decreases with the movement of clouds.

As can see from Fig. 6, when regular clouds pass through the PV array from top to bottom uniformly, the output power of the PV array becomes smaller and smaller with the increase of shadow, moreover there are multiple local extremum points in the P-U characteristic curves of the PV array. With the increase of shadow, the local extremum appears on the side of the low-voltage, which is caused by the uneven illumination of the series branches.

As can see from Fig. 7, when the irregular shadow pass through the PV array from left to right at a certain speed, the output power is firstly decreased and then increased. Moreover, as the shadow moves, there continually appear local extremum points on the left side (namely the low-voltage side), and there are several peaks in the P-U characteristic curve.



(a)

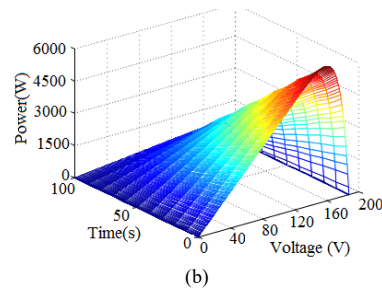


Figure 5. Regular clouds passing through the PV array from left to right

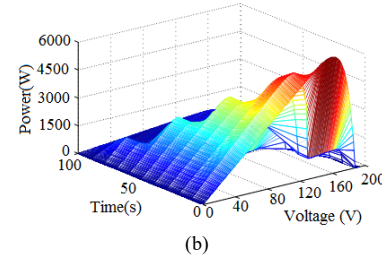
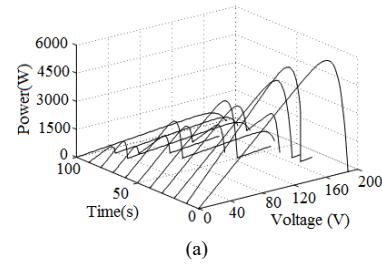


Figure 6. Regular clouds passing through PV array from top to bottom

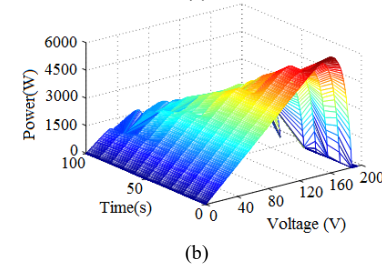
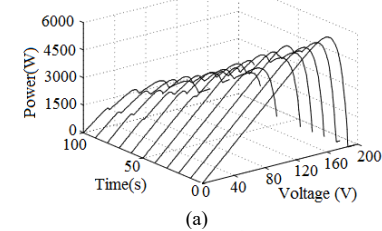


Figure 7. Irregular clouds passing through PV array

The simulation results show that the output characteristic curve of the PV array under time-varying shadow changes with variation of characteristic curves of each series branch. The output characteristic curve of the PV array is generally affected by the time-varying shadow from the high-voltage side firstly. With the increase of shadow, the light intensity of more PV modules is lower than the standard light intensity, and the local extremum point is constantly produced on the left side (namely the low-voltage side).

6. Conclusions

In order to study the output characteristics of the PV array under time-varying shadow, the time-varying shadow is divided into three kinds of variation cases considering the actual cloud movement, and the output characteristics curves of the PV array in three cases are obtained, respectively. The moving state of extremum point in the process of shadow changing is analyzed, the conclusions are as follows:

1) When the shadow is uniformly distributed to the parallel branch, the characteristic curve of the PV array does not appear multiple local extremum points.

2) When the series branch is shaded by shadow with different light intensity, the P-U characteristic curve has n local peak points if the PV modules on the series branch are subjected to n different illuminate.

3) For a PV array with $m \times n$ modules, there were at most n subranges in the PV array, and the number of extreme points in each subrange is not more than one, so the output characteristic curve has n local extremum points at most.

4) If there are multiple local extremums in the output characteristic curve of the PV array, the voltage difference at each peak point is about $0.8 \times U_{soc} \times n$ and n is a positive integer.

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