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MATLAB-based DC voltage superposition principle to study the output characteristics of PV array at partial shading

***Abstract**. Power–voltage characteristics of large scale photovoltaic (PV) arrays at partial shading are characterized by multiple steps and peaks. Most of the existing schemes are unable to accurately predict the output performance of PV array under these conditions. A Matlab-based DC voltage superposition principle is used in studying the output characteristic of a PV array under a non-uniform irradiation due to partial shading. It is observed that, for a given PV array configuration, the actual maximum power point can be gained by using the DC voltage superposition principle. The method has been experimentally validated by using several illustrative examples.*

***Streszczenie.** W artykule opisano metodę wyznaczania charakterystyki moc-napięcie dla matryc fotowoltaicznych w warunkach nierównomiernego naświetlenia, na podstawie zasady superpozycji napięć DC w programie Matlab. Korzystając z tej metody można określić punkt mocy maksymalnej, co wykazano badaniami eksperymentalnymi. (**Wyjściowa charakterystyka matrycy fotowoltaicznej w warunkach częściowego zacienienia – zasada superpozycji napięć DC z wykorzystaniem pakietu Matlab**)*

Keywords: PV array; Maximum Power Point Tracking; Partial shading; DC voltage superposition.
Słowa kluczowe: matryca fotowoltaiczna, śledzenie punktu mocy maksymalnej, częściowe zacienienie, superpozycja napięć DC.

Introduction

The ever-increasing demand for conventional energy sources like coal, natural gas and oil is driving society towards the research and development of alternate energy sources. Many such renewable energy sources like wind energy, solar thermal, PV and biomass energy are now well developed, cost effective and are being widely used, which are in their advanced developmental stage. The primary reason for solar energy has become one of the most promising sources of energy is solar energy is free and sustainable [1]. Maximum power point tracking (MPPT) control is used to maximize the output power of the PV array. Many papers have been reported in relation to MPPT. However, the current–power (I–P) curve sometimes shows multi-local maximum point mode under non-uniform insolation conditions [2]. The MPPT method is usually an essential part of a PV power generation system, because of the nonlinear characteristics of the PV array. The conventional MPPT methods (e.g., Perturbation and Observation (P&O), incremental conductance (IncCond), Ripple Correlation Control (RCC), two-mode, etc.) are very effective for tracking the MPP at same irradiation, however, which can not be used to track the maximum power point of PV system under partial shading conditions [3].

Current–voltage and power–voltage characteristics of large PV arrays under partially shaded conditions are characterized by multiple steps and peaks [4]. In these reasons, tracking the maximum power point (MPP) is difficult under the partial shading or non-uniform conditions [5]. Rapidly changing shadow conditions increase the difficulty of maximum power point tracking (MPPT) [6]. Over the years, several researchers have studied the output characteristics of PV array at partial shading, these can render accurate results, though at the expense of complex modeling, more computation time, and higher memory requirement, etc [7-8].

This paper suggests that a novel direct current (DC) voltage superposition (DCVS) method is used to enhance the knowing and predict the actual MPP of a given PV array under various weather and partially shaded conditions. It can be used as a tool to study the effect of varying temperature and irradiation and shading. Firstly, the usefulness of the proposed DCVS method is simulated by using Matlab, then which is demonstrated with many illustrative examples. It is very important to develop a novel MPPT method, especially for partial shading conditions.

Output Characteristic of PV Array at Partial Shading

The PV cells can transform the solar energy into electrical energy. The instantaneous output characteristic of PV cell depended on the temperature and radiance at that time, which is nonlinear under uniform irradiation or partially shaded conditions, which have been described in a variety of literature.

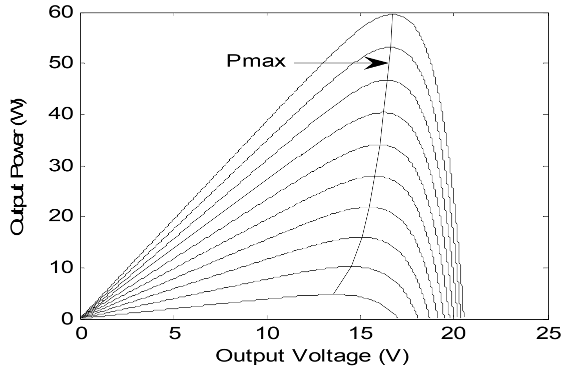

Fig.1. The output characteristic of PV at uniform irradiation

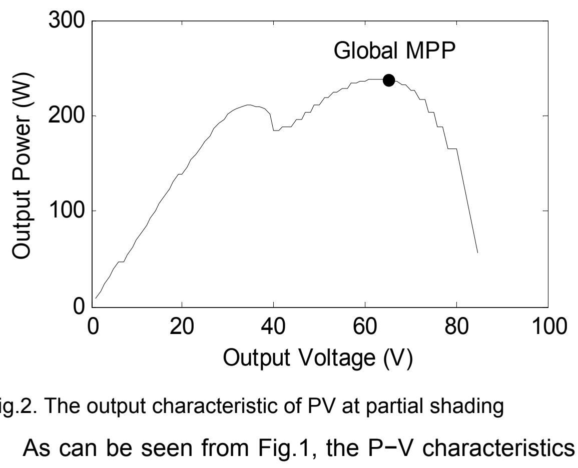

Fig.2. The output characteristic of PV at partial shading

As can be seen from Fig.1, the P−V characteristics and $P\max$ curve is displayed when the irradiation is changed from $100W/m^2$ to $1KW/m^2$ at temperature 45^oC. There is the only one MPP exists in the nonlinear curve at special irradiation and fixed temperature. The conventional MPPT method can easily track MPP, such as P&O method, IncCond method, and fuzzy logic method, and so on. For example, the conventional P&O method can track MPP under uniform radiation conditions, which has been used in some real and small scale PV system.

It is observed that P–V curve in Fig.2 has two MPP, which is called the local peaks, and there are only one is the real global peak. The conventional MPPT methods can not track the real global MPP under partially shaded conditions.

The fundamental reason is that the output performance of PV array at partial shading is different with the changing of shading, and it is very difficult to gain the optimal output voltage and current of PV array at that time. So the accurate prediction of output characteristic and optimal voltage and current becomes very important to rapidly track the real global MPP. And most of the existing schemes are unable to accurately predict the output performance of PV array under these conditions. So this paper proposes a novel algorithm to predict the global power peak under partially shaded conditions.

Proposed Method

A PV array consists of $N_{sM} \times N_{pM}$. PV modules and the output characteristic of each module are similar at the same temperature and radiation. Here, N_{sM} PV modules are connected in series, N_{pM} assemblies are connected in parallel. The output voltage of an assembly is similarly equal to N_{sM} times of the output voltage of individual module in the series, and the output current of a series assembly is equal to the minimum value of individual module in the series. The total current of the PV array is equal to N_{pM} times of the output current of individual assembly in the parallel at uniform irradiation. The output voltage is similarly equal to the minimum value of the output voltage of individual assembly at same radiation.

Under partially shaded conditions, the current available in a series connection of PV modules is limited by the current of the PV module which is less illuminated. Certainly, the bypass diode can eliminate the effect. Furthermore, the output voltage of individual assembly can be non-uniform due to the partial shading. The output characteristics of large PV arrays under partial shading conditions have multiple maximum power points, which make the tracking of the actual MPP a difficult task. A useful tool is important to understand and predict the actual MPP of a given PV array under various weather and shading conditions.

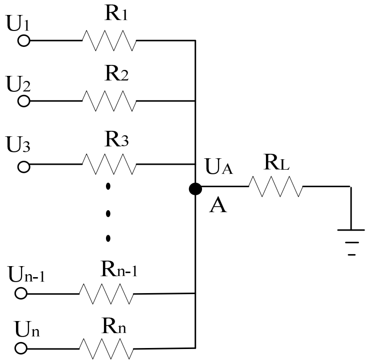

Fig.3. DCVS principle schematic diagram

The DCVS principle is generally used to supply power with an electric circuit, and a simple principle illustration can be seen from Fig.3. There are n DC voltage sources and n pure resistances, and single pure load is connected in a supply circuit. If $U_1 = U_2 = \cdots U_{n-1} = U_n$ and $R_1 = R_2 = \cdots = R_{n-1} = R_n$, then the current in the n branch circuits are equal and $U_A = U_i$. If, however, $U_1 \neq U_2 \neq \cdots \neq U_n$ and $R_1 \neq R_2 \neq \cdots \neq R_n$, then U_A is expressed as equation (1).

$$\forall i \in [1,n], \; U_A = \sum_{i=1}^{n} U_i^{'} \tag{1}$$

Here, $U_i^{'}$ is the individual function of the voltage source U_i. The individual function $U_i^{'}$ is defined as follows

$$U_i^{'} = \frac{R_1 // R_2 // \cdots // R_{i-1} // R_{i+1} // \cdots // R_n}{R_i + R_1 // R_2 // \cdots // R_{i-1} // R_{i+1} // \cdots // R_n} U_i \tag{2}$$

For the individual function $I_i^{'}$ can be written as equation (3). Here, R_i is the resistance of i th series assembly.

$$I_i^{'} = \frac{U_i - U_A}{R_i} \tag{3}$$

According to the above mention, if the U_i is seen as the output voltage of i th series assembly, then the output voltage and output current can be gained under same irradiation conditions. Here, R_i and U_A is seen as the series resistance of i th series assembly and the output voltage of a given PV array, respectively. When the PV array is in open-circuit condition, then $U_A \approx U_i$, and when the PV array is in short-circuit condition, then $I_A \approx n \times I_i$. Furthermore, the output characteristic of i th series assembly should meet the equation (4). Here, I_{sc}, I_o, and N is the shorted circuit current, reverse saturation current, and diode factor of i th series assembly, respectively. q is the electron charge, k is Boltzmann's constant, and T is the Kelvin temperature solar arrays panel.

$$I_i = I_{sc} - I_o \exp[\frac{q}{NkT}(U_i)] \tag{4}$$

If, however, the PV array is partially shaded, when the PV array is shorted, then $I_A \neq n \times I_i$. The result has been described in several researchers such as literature [4] [7].

Simulation and Analysis

For further discussion, a simple example of the shaded PV array is considered, and the simulation model was tested with an actual PV array which has been described in the literature [4], comprising three assemblies, each with six series-connected PV modules, each having a rating of $P_{max} = 38W$, $I_{MPP} = 2.29A$, $V_{MPP} = 16.6V$, $I_{sc} = 2.55A$, and $V_{OC} = 21.5V$ at an irradiation level of $1kW/m^2$ and $25^{o}C$ temperature. In the first series assembly, two modules are shaded, while in the second series assembly, three modules are shaded.

If the output voltage for third assembly is U_3, thus the output voltage U_1 and U_2 at partial shading is 2/3 and 1/2 as compare with U_3, respectively. And, the resistances for first and second assembly at partial shading are 2/3 and 1/2 to compare with R_3, respectively. The individual functions $U_i^{'}$ according to equation (2) are all equal to 2/9U_3. Then the individual functions $I_i^{'}$ according to equation (3) are 5/9, 1/3, and 7/9 of U_3/R_3, and the total shading current I_P is equal to $15U_3/9R_3$, so the $I_3^{'}$ has a share of 7/15 of as compared with the share is 1/3 of the total uniform irradiation current I_U , thus the $I_P = 5I_U/7$. Finally, the individual functions $I_i^{'}$ are equal to 5/21, 1/7, and 1/3 of I_U , respectively. According to the above mention, Fig.4 shows the $I-U$ curves of simulated and experimental results, obtained using the developed method. It is observed that the simulated results closely match the experimental values. If the shading condition for PV array is known, the proposed method is expedient to acquire the most approximate output characteristic of the PV array.

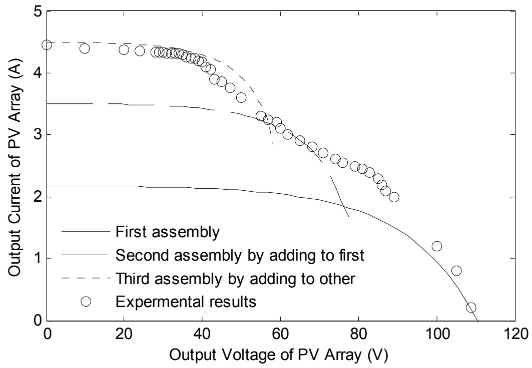

Fig.4. Simulation results

Experimental Results

Fig.5. Experimental test panel

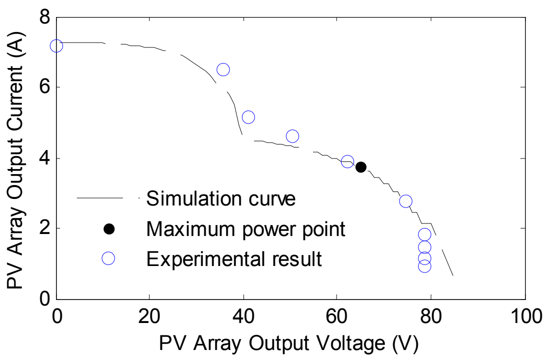

Fig.6. Experimental test results

In order to prove the validity of the proposed DCVS method, an easy testing is put into effect by using six PV modules, which comprising two assemblies, each with three series-connected PV modules, and the maximum output power of 1kW and open circuit voltage of 120V and short circuit current of 11.6A and optimal output voltage of 96V and output current of 10.4A at $25^{o}C$ and $1kW/m^2$, as shown in Fig.5.

Fig. 6 shows the simulated and experimental results. The shading effect was artificially generated by covering three modules, and there is one of the first groups and two of the second groups with black cloth, respectively. It is observed that the simulated results closely match the measured values. The average solar irradiation on the PV array for the simulation model was considered as $900W/m^2$ that is in accordance with the solar irradiation at 10:30 A.M. on November 12 at Taiyuan, China. The discrepancies between simulation and measure curves are very small, which proves that the proposed method is feasible. Furthermore, the errors at some points may be due to two reasons: 1) the measurement error over a time span and 2) voltage drop across the diode is neglected in this simulation.

Conclusions

A novel method to obtain the $I-U$ characteristics of a PV array at partial shading is described which based on a comprehensive research of output characteristic of a partially shaded PV array, and the DCVS principle is used to calculate the current of shaded assembly. It is demonstrated that, simulated and experimental results has been presented the availability of the proposed method, which can be used as a tool to investigate the effect of output at different partial shading.

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