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A Study on the Output Characteristic of Photovoltaic Array under Partially Shaded Conditions

Le Thi Minh Tam[1, a], Nguyen Van Duong[2], Nguyen Thanh Tien[3], Nguyen Viet Ngu[1,b]

[1]Faculty of Electronic and Electrical Engineering, Hung Yen University of Technology and Education, Khoai Chau, Hung Yen, Vietnam
[2]Department of Education & Training, Hanoi, Vietnam
[3]Le Qui Don Technical University, Hanoi, Vietnam
[a]email: leminhtam77@yahoo.com, [b]email: ngunguyenviet77@gmail.com

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Abstract. Efficiency of Photovoltaic (PV) array is affected by surface temperature, solar irradiance, shadow and shape of the PV array. Under partially shaded conditions, the maximum power point tracking method will be hardly controlled since the output power characteristic of the PV array is complex with many spikes. In the present study, characteristics of PV array were therefore established under partially shaded conditions by using Matlab/Simulink. The output characteristics of the PV array under partially shaded conditions were calculated and analyzed. These output characteristics significantly depend on the solar irradiance, surface temperatures, cases of shadows, configurations of the PV array, and numbers of PV modules under partial shadow. The present results are good to designate a PV power generation system by using the power point tracking method.

I. Introduction

PV array power generation system is a clean power electricity source among the various renewable energy systems. The PV array generation control systems are important and need to be improved the efficiency and developed the reliability [1][2]. In order to have maximal operating efficiency for the PV array system, the PV arrays are designed and installed complying with following principles. There are no high buildings, high trees, cover objects and so on from surrounding area etc. In fact, it is very difficult to have these areas because of the complexity of ambient environment and centralized architecture. The partial shadows such as the cover in full or in part of the shifting cloud, high building are obviously existed. In other words, efficiency of the PV arrays is affected by those partial shadows. The PV array systems should be designed under shadow condition and optimized with the construction of PV array system.

A PV array is composed of several PV modules connected in series-parallel to get the desired voltage and current. Since the PV modules in a PV array have different characteristics under partially shaded condition, the total of output powers of each PV modules will be decreased. The ouput power of this PV array is decareased. There are significant differences between output power of the PV array under no shadow and that under the partially shaded condition. Moreover, mathematical model and output characteristic of the PV array are varied when the position of partial shadow on this PV array varies. In other words, the output power of a PV array significantly decreases when current-voltage (*I-V*) curves of PV cells are not identical [3][4][5].

II. Mathematical model of PV cell under partially shader condition

A. Mathematical model of PV cell under partially shaded condition with no effect of varying the surface temperature

1. Mathematical model of parallel-connected PV cell under partially shaded condition

A PV module is composed of several PV cells connected in parallel, the circuit of parallel-connected PV cell is shown in Fig.1.

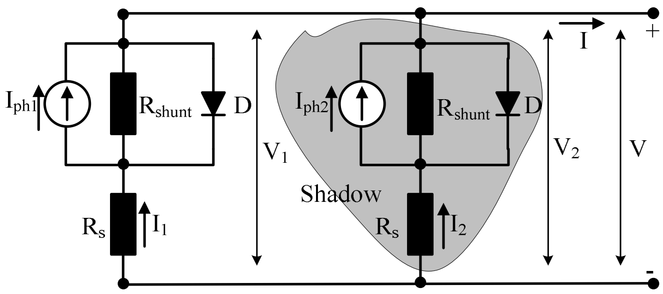


Fig.1. Circuit of parallel-connected PV cell

Assume that the PV cell 1 has no shadow, whereas PV cell 2 is shaded with shaded ratio α, that is given as:

$$\alpha = 1 - S_{behind} / S \tag{1}$$

where S is solar irradiance and S_{behind} is solar irradiance behind shaded object.

In Fig.1, currents I_1 and I_2 in PV cells 1 and 2, respectively, are expressed as:

$$I_1 = I_{ph1} - I_0\left[\exp\left(\frac{qV_1}{nkT}\right) - 1\right] \tag{2}$$

where photovoltaic-current I_{ph1} in PV cell 1 is:

$$I_{ph1} = SI_{ph0} / 1000 \tag{3}$$

and $$I_2 = I_{ph2} - I_0\left[\exp\left(\frac{qV_2}{nkT}\right) - 1\right] \tag{4}$$

where photovoltaic-current I_{ph2} in PV cell 2 is:

$$I_{ph2} = \frac{(1-\alpha)S}{1000} I_{ph0} \tag{5}$$

where V_1 and V_2 are voltages of the PV cells 1 and 2, respectively. I_{ph0} is photocurrent under standard test conditions. q is the electronic charge (q = 1.602 × 10^{-19} C), n is diode ideality factor, I_0 is the saturation current of diode, k is Boltzmann's constant (k = 1.38 × 10^{-23} J/K), T is temperature on cell surface (K).

In Fig.1, the mathematical model of the parallel-connected PV cell is:

$$V = V_1 = V_2 \tag{6}$$

$$I = I_1 + I_2 = \frac{(2-\alpha)S}{1000} I_{ph0} - 2I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right] \tag{7}$$

2. Mathematical model of series-connected PV cell under partially shaded condition

A PV module is composed of several PV cells connected in series, the circuit of series-connected PV cell is shown in Fig.2.

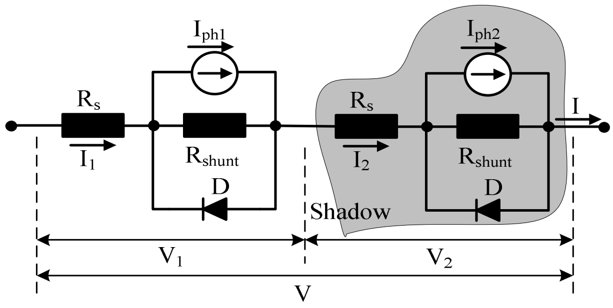


Fig.2. Circuit of series-connected PV cell

In Fig.2, the mathematical model of the series-connected PV cell is:

$$I = I_1 = I_2 \tag{8}$$

$$V = V_1 + V_2 \tag{9}$$

From equations (2), (3), (4), and (5), equation (8) therefore is rewritten as follows:

$$I_{ph1} - I_0\left[\exp\left(\frac{qV_1}{nkT}\right) - 1\right] = I_{ph1} - \frac{\alpha S}{1000} I_{ph0} - I_0\left[\exp\left(q\frac{V - V_1}{nkT}\right) - 1\right] \tag{10}$$

$$I = I_{ph1} - \frac{\alpha S}{1000} I_{ph0} - I_0\left[\exp\left(q\frac{V - V_1}{nkT}\right) - 1\right] \tag{11}$$

Voltage V_1 of the PV cell 1 is:

$$V_1 = \frac{nkT}{q}\ln\left(\frac{I_{ph1} - I + I_0}{I_0}\right) \tag{12}$$

With equation (11) replaced by equation (12), we obtained the mathematical model of the series-connected PVcell as follows:

$$I = I_{ph1} - \frac{\alpha S}{1000} I_{ph0} - I_0\left[\exp\left(\frac{qV - nkT\ln\left((I_{ph1} - I)/I_0 + 1\right)}{nkT}\right) - 1\right] \tag{13}$$

From equations (7) and (13), it is clear that the output characteristics of the PV cell, which have complex nonlinear relation, were changed under the partially shaded condition with no effects of varying the surface temperature.

B. Mathematical model of PV cell under partially shaded condition with effect of varying surface temperature

Surface temperature on the PV cell will be changed if the solar irradiance on the PV cell varies. The output characteristic of the PV cell, therefore, is also changed. Moreover, the relationship between the solar irradiance and the temperature difference of air and surface of PV cell is linear [6]. Then, the approximate equation is given as follows:

$$T = T_{\text{air}} + (NOCT - 20)/800S \tag{14}$$

where *NOCT* is nominal operating cell temperature, T_{air} is air temperature (^{o}C).

NOCT is defined as the temperature that is reached by open-circuited cell in a module under the representative conditions such as, solar irradiance on cell surface is 800W/m^2, air temperature is 20°C, and wind velocity is 1 m/s. The best module operated at *NOCT* of 33°C, the worst module at *NOCT* of 58°C, and the typical module at *NOCT* of 48°C. In the present study, let us suppose the value of *NOCT* is 48°C, the surface temperature of the PV cell is represented as:

$$T = T_{\text{air}} + (48-20)/800S \tag{15}$$

or: $$T = T_{\text{air}} + 0.035S \tag{16}$$

The surface temperature of the PV cell under the partially shaded condition with shaded ratio α is given as:

$$T_{\alpha} = T_{\text{air}} + 0.035(1-\alpha)S \tag{17}$$

It is clear that the solar irradiance deeply affected the surface temperature of the PV cell. The surface temperatures of the PV cell were not uniform under the partially shaded condition. The output characteristic of the PV cell is significantly complicated.

1. Mathematical model of parallel-connected PV cell under partially shaded condition

By using the Fig.1 for considering the problem, with equations (2) and (4) respectively replaced by (16) and (17), we obtained:

$$I_1 = \frac{S}{1000} I_{ph0} - I_0 \left[\exp\left(\frac{qV_1}{nk\left(T_{\text{air}} + 0.035S\right)} \right) - 1 \right] \tag{18}$$

$$I_2 = \frac{(1-\alpha)S}{1000} I_{ph0} - I_0 \left[\exp\left(\frac{qV_2}{nk\left(T_{\text{air}} + 0.035(1-\alpha)S\right)} \right) - 1 \right] \tag{19}$$

The mathematical model of this PV cell under the partially shaded condition is given as:

$$V = V_1 = V_2 \tag{20}$$

$$I = I_1 + I_2 = \frac{(2-\alpha)S}{1000} I_{ph0} - I_0 \exp\left(\frac{qV}{nk\left(T_{\text{air}} + 0.035S\right)} \right) - I_0 \exp\left(\frac{qV}{nk\left(T_{\text{air}} + 0.035(1-\alpha)S\right)} \right) + 2I_0 \tag{21}$$

2. Mathematical model of series-connected PV cell under partially shaded condition

By using the Fig.2 for considering the problem, with equation (8) replaced by (18), we obtained:

$$I = I_1 = \frac{S}{1000} I_{ph0} - I_0 \left[\exp\left(\frac{qV_1}{nk\left(T_{\text{air}} + 0.035S\right)} \right) - 1 \right] \tag{22}$$

or: $$V_1 = \frac{nk\left(T_{\text{air}} + 0.035S\right)}{q} \ln\left(\frac{SI_{ph0}/1000 - I + I_0}{I_0} \right) \tag{23}$$

With equation (19) replaced by (9), we obtained:

$$I = \frac{(1-\alpha)S}{1000} I_{ph0} - I_0 \left[\exp\left(\frac{q\left(V - V_1\right)}{nk\left(T_{\text{air}} + 0.035(1-\alpha)S\right)} \right) - 1 \right] \tag{24}$$

With equation (24) replaced by (23), we obtained mathematical model of the series-connected PV cell under the partially shaded condition:

$$I = \frac{(1-\alpha)S}{1000} I_{ph0} - I_0 \left[\exp\left(\frac{qV - nk\,(T_{air} + 0.035S)\ln\left(\frac{SI_{ph0}/1000 - I + I_0}{I_0}\right)}{nk\,(T_{air} + 0.035(1-\alpha)S)} \right) - 1 \right] \quad (25)$$

From equations (21) and (25), it is clear that the output characteristic of the PV cell is changed and that is complex nonlinear under the partially shaded condition with effect of varying surface temperature.

III. Simulation model and analysis of PV array under partially shaded condition

In the present study, four partially shaded conditions, which are illustrated in Fig.3, were considered as follows:

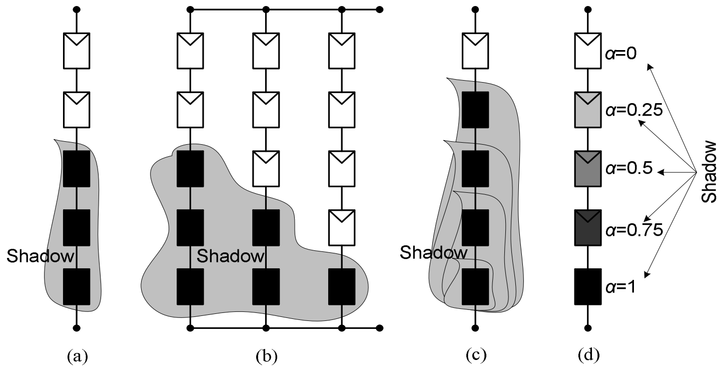


Fig.3. PV array under partially shaded conditions

(a) Series-connected PV array under partially shaded conditions;
(b) Parallel-connected PV array under partially shaded conditions;
(c) Series-connected PV array with different numbers of PV module under partially shaded conditions;
(d) Series-connected PV array with differently shaded ratios under partially shaded conditions.

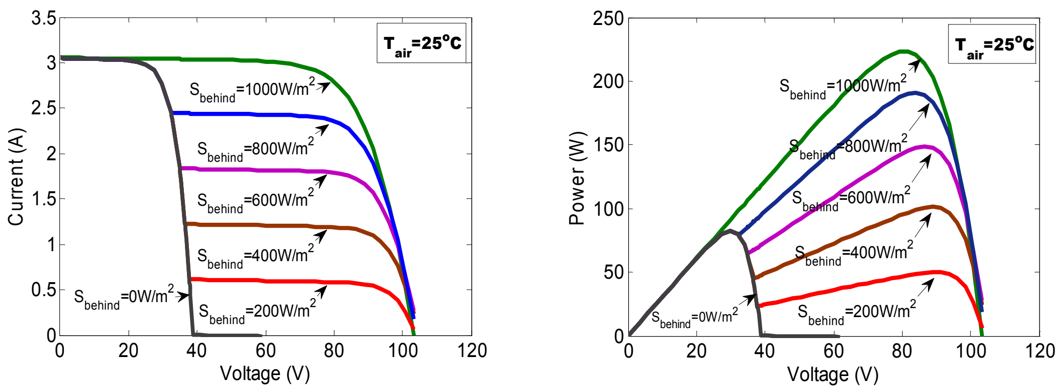
A. Simulation and analysis of characteristic of PV array under partially shaded conditions with no change of surface temperature

Let us assume that air temperature T_{air} has not varied and equals 25°C; short current of each PV module is equal to 3A; standard solar irradiance S=1000W/m^2.

In Figs.3(a) and 3(b), shaded ratios α are 1, 0.8, 0.6, 0.4, 0.2, and 0 corresponding to solar irradiances behind shaded object S_{behind} are 0W/m^2, 200W/m^2, 400W/m^2, 600W/m^2, 800W/m^2, and 1000W/m^2. The simulation results are presented in Figs. 4-5.

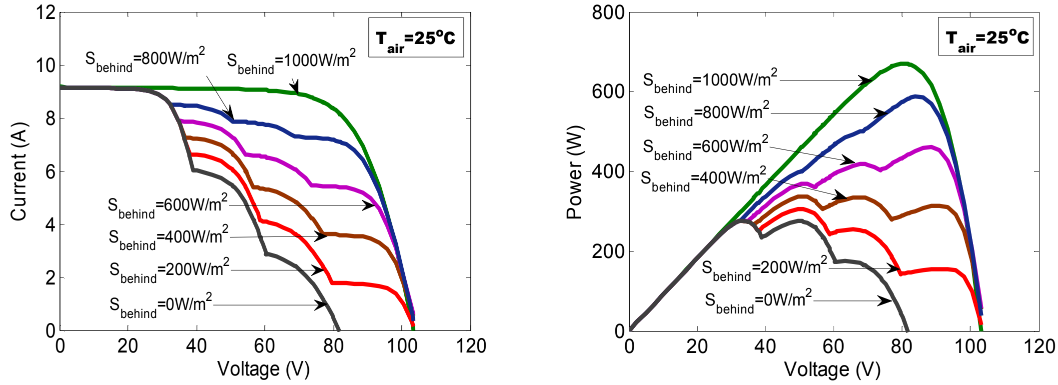
In Fig.3(c), shaded ratios α are 0.2 corresponding to solar irradiances behind shaded object S_{behind} are 800W/m^2. The simulation results are presented in Fig.6.

In Fig.3(d), shaded ratios α are 1, 0.75, 0.5, 0.25, and 0 corresponding to solar irradiances behind shaded object S_{behind} are 0W/m^2, 250W/m^2, 500W/m^2, 750W/m^2, and 1000W/m^2. The simulation results are presented in Fig.7.



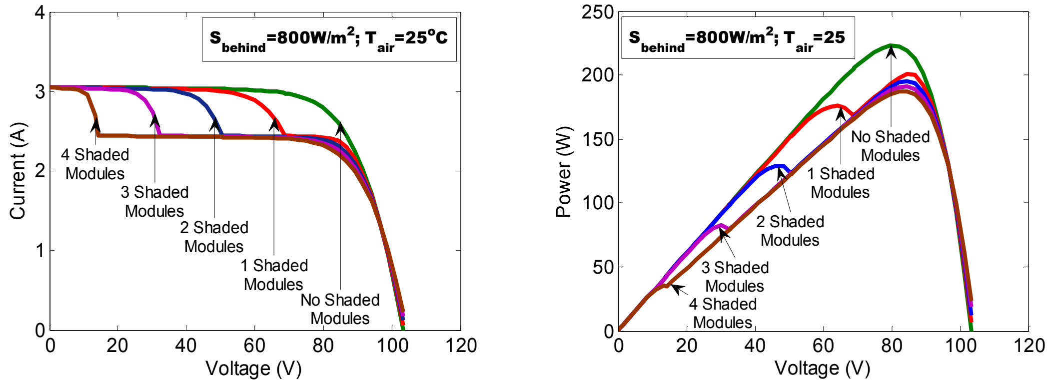
(a) *I-V* characteristic (b) *P-V* characteristic

Fig.4. Output characteristics of series-connected PV array under partially shaded conditions with no change of surface temperature.



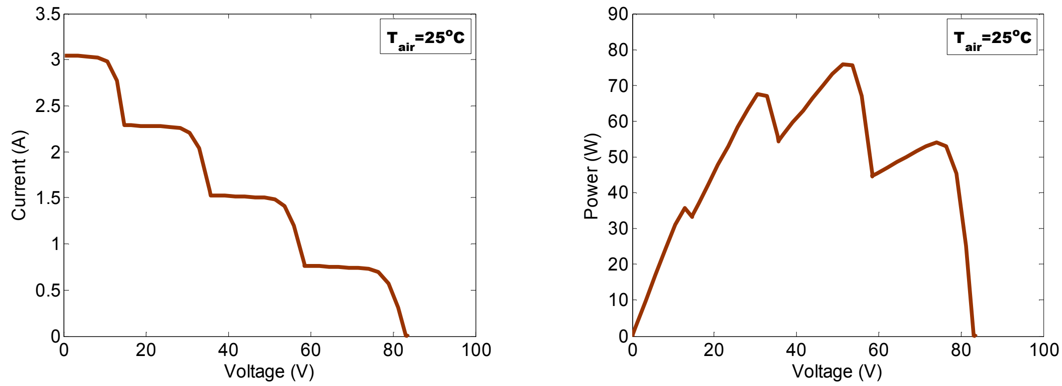
(a) *I-V* characteristic (b) *P-V* characteristic

Fig.5. Output characteristics of parallel-connected PV array under partially shaded conditions with no change of surface temperature.



(a) *I-V* characteristic (b) *P-V* characteristic

Fig.6. Output characteristics of series-connected PV array with different numbers of PV modules under partially shaded conditions with no change of surface temperature.



(a) *I-V* characteristic (b) *P-V* characteristic

Fig.7. Output characteristics of series-connected PV array with differently shaded ratios under partially shaded conditions with no change of surface temperature.

Fig.4 shows the output characteristics of series-connected PV array under partially shaded conditions with no change of surface temperature. The output characteristics of PV array were changed under the partially shaded conditions. The trend of output characteristics was the same, but their magnitudes were different. PV array currents are different due to the differently shaded ratios. Therefore, ouput power occurred many spikes.

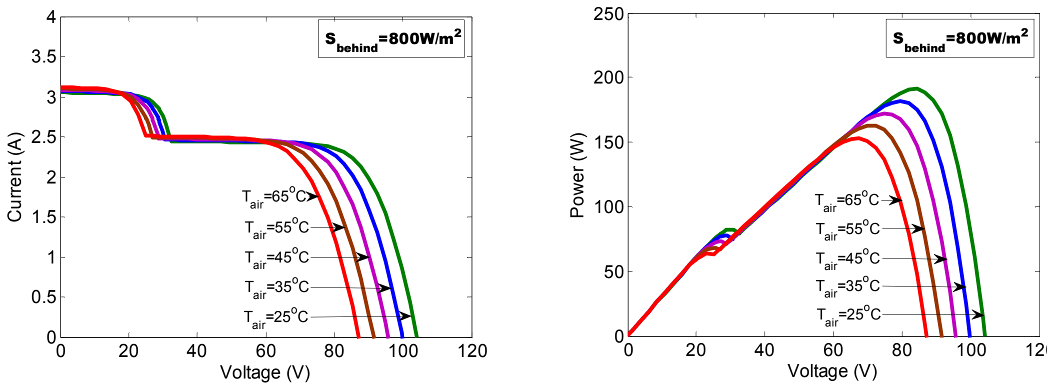
Fig.5 shows the output characteristics of parallel-connected PV array under partially shaded conditions with no change of surface temperature. Since numbers of PV modules, which is shaded, in three series-connected branchs of the PV array is different, electric shunt time of bipass diode is also different. In this case, the shape of current in each brach is different, then, ouput power occurred many spikes.

Fig.6 shows the output characteristics of series-connected PV array with different numbers of PV modules under partially shaded conditions with no change of surface temperature. The off-load voltage and short current are not affected by solar irradiance. Similar to the case of parallel-connected PV array under partially shaded conditions, ouput power also occurred many spikes.

Fig.7 shows the output characteristics of series-connected PV array with differently shaded ratios under partially shaded conditions with no change of surface temperature. Magnitude of current in each PV module is different. Moreover, conductive time of each bypass diode is different. Therefore, the shape of current in each brach is different and ouput power occurred many spikes.

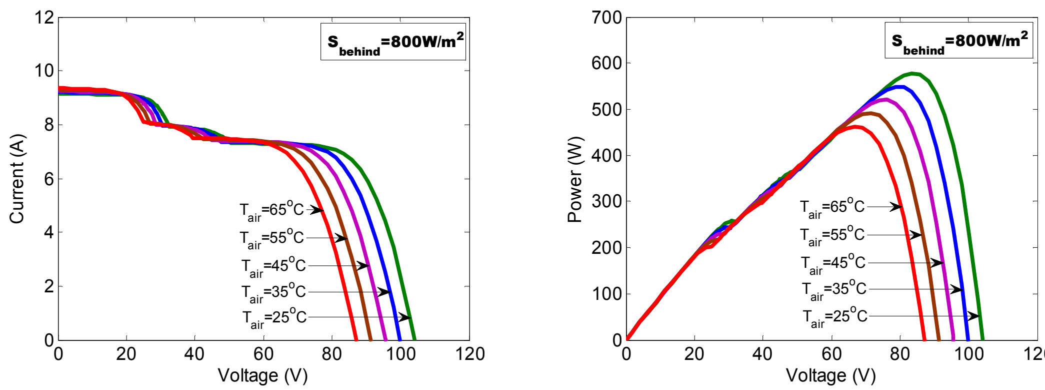
B. Simulation and analysis of characteristic of PV array under partially shaded conditions with change of surface temperature

In order to consider effects of solar irradiance on surface and output characteristics of PV array, Figs.3(a) and 3(b) show effect of solar irradiance on surface temperature of the PV array with shaded ratio α of 0.2 (S_{behind} =800W/m^2). Concurrently, Fig.3(d) shows effect of solar irradiance on surface temperature of the PV array with differently shaded ratios α of 1, 0.75, 0.5, 0.25, and 0 corresponding to solar irradiances behind shaded object S_{behind} are 0W/m^2, 250W/m^2, 500W/m^2, 750W/m^2, and 1000W/m^2. The simulation results are presented in Figs.8-10.



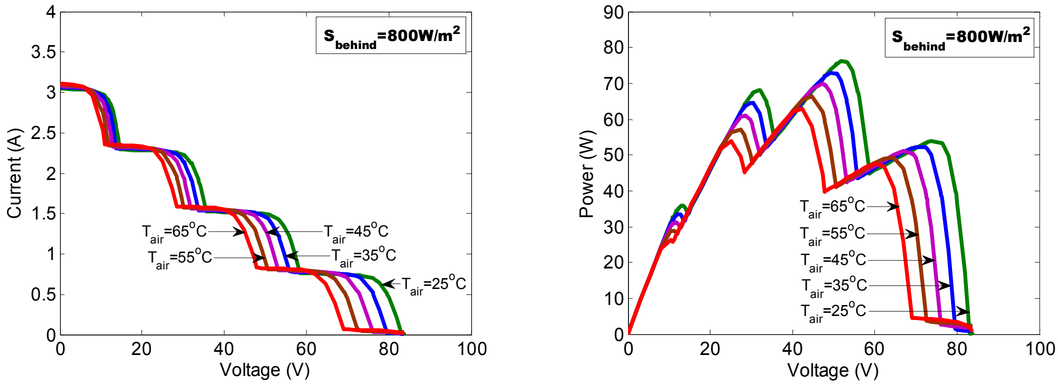
(a) *I-V* characteristic (b) *P-V* characteristic

Fig.8. Output characteristics of series-connected PV array under partially shaded conditions with change of surface temperature.



(a) *I-V* characteristic (b) *P-V* characteristic

Fig.9. Output characteristics of parallel-connected PV array under partially shaded conditions with change of surface temperature.



(a) *I-V* characteristic (b) *P-V* characteristic

Fig.10. Output characteristics of series-connected PV array with differently shaded ratios under partially shaded conditions with change of surface temperature.

Figs.8-10 show the output characteristics of PV arrays under partially shaded conditions with change of surface temperatures of 25°C, 35°C, 45°C, 55°C, and 65°C. The off-load voltage decreased and short current slightly increased with increasing surface temperature. Concurrently, the position of maximum power has been changed with varying surface temperature.

IV. Conclusion

The simulation models of the PV array under partially shaded conditions were designed by Matlab/Simulink. The output characteristics of the PV array under partially shaded conditions were calculated and analyzed. These output characteristics significantly depend on the solar irradiance, surface temperatures, cases of shadows, configurations of the PV array, numbers of PV modules under partial shadow. The present results are good to designate a PV power generation system by using the power point tracking method.

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