ANALYSIS OF SHADED SERIES AND PARALLEL CONNECTED PHOTOVOLTAIC MODULES AT UYO, NIGERIA

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ABSTRACT

This work analyses the performance of shaded series and parallel connected photovoltaic (PV) modules at Uyo, Nigeria. A model that represents 36 cells PV module under partial shading conditions has been used to test several shading profiles. The effect of shading varies from one to many cells on the module rows, when cells are shaded from 1 to 18, the power drops drastically. This demonstrates how solar panels perform under shading including the diminished ability to produce electricity under this condition. Therefore, photovoltaic modules should be mounted away or above tall trees and buildings to avoid shading.

INTRODUCTION

A photovoltaic (PV) system is a solid state device that converts solar energy into electricity, so its performance depends on insolation. Performance of a series connected string of solar cells is adversely affected when some cells are partially shaded. Shadows fall over some cells due to tall tree leaves and neighbouring tall buildings. The study of partial shading is very important because the trend now is to integrate the solar PV array at the design level in the building. For a series connected string of solar cells, all the cells carry the same current. Under shade a few cells produce less photon current but these cells are also forced to carry the same current as the other fully illuminated cells. The shaded cells get reverse biased, acting as loads, draining power from fully illuminated cells. The impact of partial shading on the PV array performance has been studied by Karatepe *et al.*, (2007), Rauschenbach (1971), Kaushika and Gautam (2003), Alonso-Garcia *et al* (2006).The effect of shading on varying number of cells on the power output of the shaded module has been studied (Ramaprabhan and Mathur, 2009). An equivalent circuit of a Solar Photovoltaic (SPV) module is shown in Fig. 1.

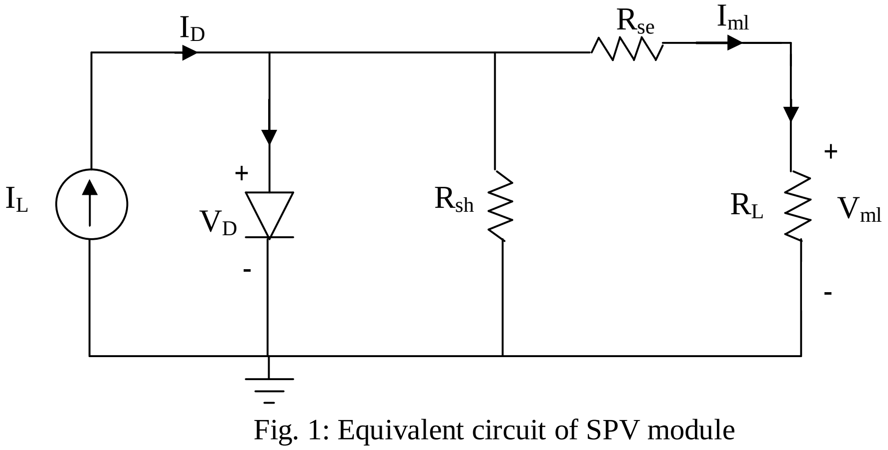

Fig. 1: Equivalent circuit of SPV module

The output current I_{ml} through the load resistance for module-1is given by

$$I_{m1} = I_L - I_o\left\{\exp\left(\frac{V_{m1} + I_{m1}R_{se}}{V_t}\right) - 1\right\} - \frac{(V_{m1} + I_{m1}R_{se})}{R_{sh}} \quad (1)$$

where V is module voltage, I is module current, I_L is the current generation by absorption of photons at short circuit, R_{se} and R_{sh} are the series and shunt resistances in the equivalent circuit of the module, I_o is diode reverse saturation current, V_t is thermal voltage (nkT/q), subscripts m_1 and m_2 are for module-1 and module-2, respectively.

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When a solar cell in a series array is under shadow in module-2, its current output is given by

$$I_s = FI_L - I_o\left\{\exp\left(\frac{V_{Ds}}{V_t}\right) - 1\right\} - \frac{V_{Ds}}{R_{shs}} \quad (2)$$

where $V_{Ds} = v_s + I_s R_{ses}$

where the photo current generated by the shaded illuminated cell is FI_L, F is the ratio of photo current generated by the shaded cell to that of the fully illuminated cell. For $F = 0$, it means fully shaded, and $F = 1$ means fully illuminated (Ramaprabhan and Mathur, 2009).

$$I_i = I_L - I_o\left\{\exp\left(\frac{V_{Ds}}{V_t}\right) - 1\right\} - \frac{V_{Di}}{R_{shi}} \quad (3)$$

where $V_{Di} = v_i + I_i R_{sei}$

Since the shaded and illuminated cells are connected in series, the same current is forced to flow through both. So in equations (2) and (3), I_i and I_s are replaced by the same I_{m2}, therefore,

$$I_{m2} = FI_L - I_o\left\{\exp\left(\frac{V_{Ds}}{V_t}\right) - 1\right\} - \frac{V_{Ds}}{R_{shs}} \quad (4)$$

$$I_{m2} = I_L - I_o\left\{\exp\left(\frac{V_{Di}}{V_t}\right) - 1\right\} - \frac{V_{Di}}{R_{shi}} \quad (5)$$

With shading, $\exp\left(\frac{V_{Ds}}{V_t}\right)$ tends to zero as the value of F decreases from 1 to 0, equation (4) becomes

$$I_{m2} = FI_L - I_o - \frac{v_s + I_{m2}R_{ses}}{R_{shs}} \quad (6)$$

For series connected modules

$$I = I_{m1} = I_{m2} = FI_L + I_o - \frac{v_s + IR_{ses}}{R_{shs}} \quad (7)$$

Rearranging equation (7), the expression for the voltage across the shaded cell v_s can be obtained as

$$v_s = (FI_L - I)R_{shs} - IR_{ses} \quad (8)$$

The power dissipated by the shaded cell is obtained using equation (8) as

$$P_{Ds} = Ixv_s = I\{(FI_L - I)R_{shs} - IR_{ses}\} \quad (9)$$

The total array output voltage is the sum of voltages across each cell operating at the same current I. So the array output voltage is expressed as

$$V = V_{m1} + V_{m2} = V_{m1} + (v_i + v_s) = V_{m1} + \left(\sum_{j=0}^{a} v_{ij} + \sum_{k=0}^{b} v_{sk}\right) \quad (10)$$

where a + b = 36 cells.

In the case of parallel connected modules

$$I = I_{m1} + I_{m2} = I_{m1} + \left(FI_L + I_o - \frac{v_s + I_{m2}R_{ses}}{R_{shs}} \right) \tag{11}$$

Then the expression for the voltage across the shaded cell v_s from Eqn. (11) can be obtained as

$$v_s = (FI_L + I_{m1} - I)R_{shs} - I_{m2}R_{ses} \tag{12}$$

Neglecting the term I_oR_{sh} in Eqns. (8) and (12) in comparison with larger terms, the power dissipated by the shaded cell is obtained from equation (12) as

$$P_{Ds} = I_{m2} x v_s = I_{m2}\{(FI_L + I_{m1} - I)R_{shs} - I_{m2}R_{ses}\} \tag{13}$$

The module output voltage V can be written as

$$V = V_{m1} = V_{m2} = \left(\sum_{j=0}^{a} v_{ij} + \sum_{k=0}^{b} v_{sk} \right) \tag{14}$$

Mismatch power loss (the loss of available power due to series and parallel connection) is defined as

$$P_{\max(mismatchlosses)} = (P_{\max(module1)} + P_{\max(module2)}) - P_{\max(array)} \tag{15}$$

where $P_{\max(module2)} = \left(\sum P_{\max(illuminatedcells)} + \sum P_{\max(shadedcells)}\right)$

The mismatch power loss in series connected array is more than that of parallel connected array (Ramaprabhan and Mathur, 2009b). Loss of power due to series and parallel connections can also be defined in terms of utilization factor (UF) as

$$UF_{(array)} = \frac{P_{\max(array)}}{P_{\max(module1)} + P_{\max(module2)}} \tag{16}$$

Analysis of shadows: The altitude α of the Sun as a function of latitude ϕ, solar declination δ and angle ω subtended by the Sun at a particular hour is given as in Duffie and Beckman (1980).

$$\sin\alpha = \sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega \tag{17}$$

The angle θ of incidence of the radiation beam on a tilted surface (module) is given as

$$\cos\theta = \cos\delta \cos\omega(\cos\gamma \sin\beta \sin\phi + \cos\phi \cos\beta) + \sin\delta(\sin\phi \cos\beta - \cos\gamma \cos\phi \sin\beta) + \sin\gamma \sin\beta \cos\delta \sin\omega \tag{18}$$

where γ is the azimuth angle of the surface and β is the panel inclination, Fig. 2.

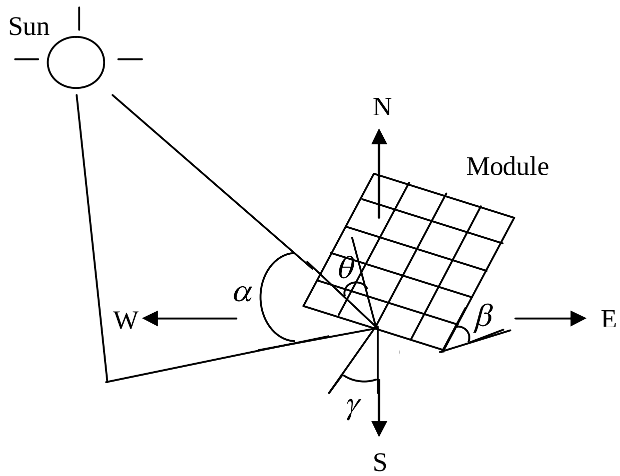

Fig. 2: Definition of Angle at a Module Surface

For a south-facing surface, $\gamma = 0$ (Passias and Kallback 1984) and Eqn. (18) reduces to

$$\cos\theta = \sin(\phi - \beta)\sin\delta + \cos(\phi - \beta)\cos\delta\cos\omega \qquad (19)$$

The PV modules used (polycrystalline silicon cells) had the following specifications at 1000Wm^{-2} solar irradiance and 25^{o}C cell temperature; maximum power of 55W (Table 1). The studies was carried out at Uyo (Lat 5^{o}2$^{/}$60N, Long 7^{o}55$^{/}$60E and altitude 38m).

Table 1: Technical specifications of UNI-SOLAR Module

S/N	Parameters	Module
1	Maximum Power	55W
2	Short circuit current (I_{sc})	3.38A
3	Rated current	3.18A
4	Max system open circuit voltage	600V
5	Open circuit voltage (V_{oc})	21.7V
6	Rated Voltage	17.0V

RESULTS AND DISCUSSION

The results obtained for power output from illuminated/unshaded and 85% shaded modules for a typical day in March at Uyo, Nigeria are presented in Fig. 3. The values of P_{max} mismatch loss and UF_{array} were about 2.24W and 0.94 respectively.

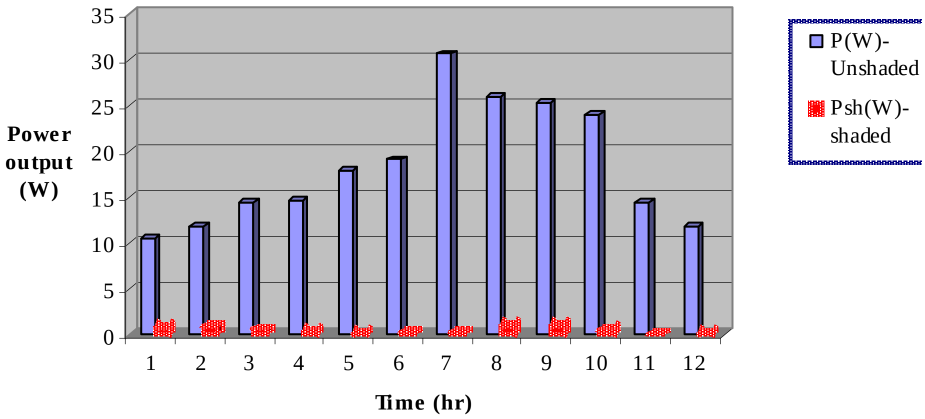

Fig. 3: Power output from 55W module per day

From Fig. 3, the power output of the unshaded / illuminated cells increased substantially from 10.0W at 8:00am in the morning to a maximum of about 30.0W at 1:00pm in the afternoon and then decreased to about 12.0W at 6:00pm in the evening of that day. The solar radiation varied from about 87.6Wm^{-2} at 8:00am in the morning to about 520.5Wm^{-2} at 1:00pm in the afternoon and then to about 38.9Wm^{-2} at 6:00pm in the evening of that day. For the shaded cells, the total output decreased drastically to about 0.9W with 85% shading due to decrease in energy input to the cells and due to increase energy losses in the shaded cells (Ramaprabhan and Mathur, 2009b). With shading the power output drops drastically. The power output decreases with increase shading of the cells. Power output at various temperatures is given in Fig. 4.

Fig. 4 shows that partial shading causes reduction of power yield of the module likely due to overheating of shaded cells and their inability to generate power. The power dissipated by the shaded cells could be substantial leading to increase in its temperature. Due to increased temperature, the cell current gets concentrated in an increasingly small region of the cell producing a hot spot. This heat build-up can damage the cell encapsulation and eventually produce module failure (Klenk 2002)

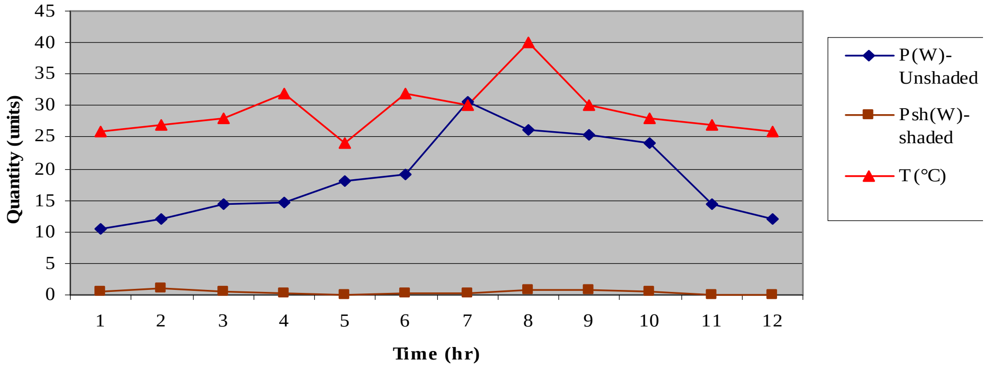

Fig. 4: Power output at various ambient temperatures

The power dissipated by the shaded cells is higher in series connected modules than in parallel connected modules. Generally, the photovoltaic system is user and environmentally friendly and home owners should be encouraged to utilize it as opposed to the use of conventional sources of energy that lead to depletion of vegetation and emit harmful pollutants into the environment affecting it negatively.

CONCLUSION

Series connected solar cells practically give a higher voltage output while the parallel connected solar cells yield more current. Since there is a substantial power loss due to shading of a series string, care should be taken to make sure that all cells connected in series receive the same illumination under different patterns of shading. This provides protection for the module and also gives a higher power output. The parallel connected array is the best possible configuration for the study at Uyo.

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