MATLAB based Modelling to Study the Influence of Shading on Series Connected SPVA

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Abstract—Partial shading has been identified as a major cause of reducing energy yield in a large solar photovoltaic array (SPVA). Partial shading may be due to due to tree leaves falling over it, birds or bird litters on the array, shade of a neighboring construction, passing clouds etc. Under partial shaded conditions the PV characteristics get more complex with multiple peaks. It is important to understand and predict them to get maximum possible power from the SPVA. This paper presents a MATLAB-based modelling and simulation scheme suitable for studying the influence of on a series connected SPVA. The conventional model is modified to include the effect of shading in the SPV module parameters for simulation study. The simulation of MPPT algorithm to track the global maximum is also presented. The model is practically validated using electronic load.

Key Words: - Solar PV array, Partial shading, Improved Model, Electronic load, Matlab

I. NOMENCLATURE

\( I_{PV}, V_{PV} \) - Solar PV module Current (A) and Voltage (V) respectively
\( I_{ph} \) - Photo current SPV module (A)
\( I_r \) - Diode reverse saturation current in the equivalent circuit (\( \mu \)A)
\( R_{se} \) - Series resistance in the equivalent circuit of the module (m\( \Omega \))
\( R_{sh} \) - Parallel resistance in the equivalent circuit of the module (\( \Omega \))
\( R_L \) - Load resistance
\( D \) - Diode used in the equivalent circuit
\( n \) - Diode ideality factor (1\( <n<2 \) for a single solar cell)
\( q \) - Electron charge (\( =1.602\times10^{-19} \) C)
\( k \) - Boltzman’s constant (\( =1.381\times10^{-23} \) J/K)
\( T \) - Temperature (Kelvin)
\( V_t \) - Thermal voltage (= nkT/q)
\( G \) - Insolation level (at reference condition G=1000 w/m²)
\( \alpha \) - Short circuit current temperature co-efficient
\( I_{sc} & V_{oc} \) - Short circuit current and open circuit voltage of the module respectively
\( V_{mp} & I_{mp} \) - Maximum power point voltage and current respectively
\( PV_{max} \) - Maximum power
\( D_b \) - Bypass diodes used in the series array configuration
ref - Additions subscripts indicate the parameters at reference conditions
\( 1,2,3 \) - Additional subscripts indicate the parameters of Panel-1, Panel-2 & Panel-3 respectively
\( V_{11}, V_{12}, V_{13} \) - Operating points of Panel-1 in series connection
\( V_{21}, V_{22}, V_{23} \) - Operating points of Panel-2 in series connection
\( V_{31}, V_{32}, V_{33} \) - Operating points of Panel-3 in series connection
\( I_1, I_2, I_3 \) - Operating point currents of series connected SPVA
\( P_1, P_2, P_3 \) - Power at operating points

II. INTRODUCTION

Solar Photovoltaic array is formed by series and parallel combination of solar modules. Therefore the SPVA performance is dependent on the behavior of the individual cells. This is critical under mismatched operating conditions like partial shading. Cells under shade absorb a large amount of electric power generated by cells receiving high insolation and convert it into heat. This heat may damage the low illuminated cells under certain conditions. To relieve the stress on shaded cells, bypass diodes are added across the modules. In such a case multiple peaks in power-voltage characteristics are observed under non uniform illumination. Classical Maximum Power Point Tracking (MPPT) methods are not effective due to their inability to discriminate between local and global maxima [1]-[4]. Nevertheless, it is very important to understand the characteristics of SPV under partial shaded conditions to use PV installations effectively under all conditions. Analog models of SPV sources at varying temperature, insolation and partial shaded conditions were presented in the literature [5]. This paper presents the improved model of SPVA which takes care about the dependence of all the parameters in the model with...
respect to insolation and temperature [6]-[8]. The model was simulated using Matlab software. The developed model was validated with experimental results. To capture the characteristics under constant insolation and temperature conditions, the experimental characteristics were obtained using linear MOSFET as an electronic load.

III. MISMATCH MODEL OF SPVA

The equivalent circuit model of a solar cell consists of a current generator and a diode plus series and parallel resistance as shown in Fig.1. The mathematical equation expressing the output current of single cell is given by equation (1)

\[
I_{pv} = I_{ph} - I_{ref} \left[ \exp \left( \frac{V_{ref} + I_{ref}R_{sh}}{V_{t}} \right) - 1 \right] \frac{(V_{ref} + I_{ref}R_{sh})}{R_{sh}} \tag{1}
\]

To get the improved model, the effect of insolation and temperature on each parameter has to be evaluated. For this, the following five reference parameters are required. They are \(V_{tref}\), \(I_{ref} \), \(I_{phref} \), \(R_{seref}\) and \(R_{shref}\) are required. To find the reference parameters it is important to know the following parameters. [9]

- At short circuit current: \(I_{PV} = I_{SC0} \), \(V_{PV} = 0\) (given in datasheet)
- At open circuit voltage: \(I_{PV} = 0\), \(V_{PV} = V_{OC0}\) (given in datasheet)
- At the maximum power point: \(I_{PV} = I_{MP0}, V_{PV} = V_{MP0}\) (given in datasheet)
- At the maximum power point: \(dP/dV_{mp}=0\)
- Under reference conditions equation (1) can be rewritten as,

\[
I_{pv} = I_{phref} - I_{ref} \left[ \exp \left( \frac{V_{ref} + I_{ref}R_{shref}}{V_{tref}} \right) - 1 \right] \frac{(V_{ref} + I_{ref}R_{shref})}{R_{shref}} \tag{2}
\]

\[
I_{sc} = I_{sc0} \left[ 1 + \alpha (T - T_{ref}) \right] & I_{sc0} = I_{pivef} \tag{3}
\]

\[
0 = I_{phref} - I_{ref} \left[ \exp \left( \frac{V_{ref} + I_{ref}R_{shref}}{V_{tref}} \right) - 1 \right] \frac{(V_{ref} + I_{ref}R_{shref})}{R_{shref}} \tag{4}
\]

\[
I_{mp} = I_{pivef} - I_{ref} \left[ \exp \left( \frac{V_{ref} + I_{ref}R_{shref}}{V_{tref}} \right) - 1 \right] \frac{(V_{ref} + I_{ref}R_{shref})}{R_{shref}} \tag{5}
\]

\[
\frac{d(I_{PV}V_{PV})}{dV} = 0 \text{ under Maximum power point condition} \tag{6}
\]

\[
\frac{d(I_{PV})}{dV} = -\frac{1}{R_{pivef}} \text{ at short circuit point} \tag{7}
\]

The five reference parameters \(I_{phref}, I_{ref}, V_{tref}, R_{seref} \) and \(R_{shref}\) can be obtained by simultaneously solving Equations (3) through (7). In the improved model, the effect of ideality factor, series and shunt resistance with respect to insolation and temperature has been added. From literature, the following relations can be obtained:

\[
I_P = G \times I_{SC} \tag{8}
\]

\[
I_{SC} = I_{sc0} \left[ 1 + \alpha (T - T_{ref}) \right] & I_{sc0} = I_{pivef} \tag{9}
\]

\[
I_r = I_{ref} \left( \frac{T}{T_{ref}} \right)^{\frac{1}{2}} \exp \left[ b \left( \frac{1}{T_{ref}} - \frac{1}{T} \right) \right] \tag{10}
\]

\[
V_r = V_{ref} \left( \frac{T}{T_{ref}} \right) \tag{11}
\]

\[
G \left[ \frac{V}{I} \exp \left( \frac{V_{ref} + I_{ref}R_{shref}}{V_{tref}} \right) + R_{shref} \right] = \frac{V_{ref} \exp \left( \frac{V_{ref} + I_{ref}R_{shref}}{V_{tref}} + R_{shref} \right)}{V_{tref}} \tag{12}
\]

\[
R_{sh} = R_{shref} \tag{13}
\]

The above equations are used to simulate the model of existing solar panel (Solkar) which consists of 36 cells in series. The simulation is carried out using Matlab software. [10]-[12], [14]

As with the connection of cells to form panels, a number of panels can be connected in series string to increase the voltage level, in parallel to increase the current level or in a combination of the two. The exact configuration depends on the current and voltage requirements of the load. Matching of the interconnected panels in respect of their outputs can maximize the efficiency of the array. The conventional PV panel is constructed of several PV cells (normally 36 cells) connected in series. In the PV power generation system, multiple PV panels are generally connected in series in order to obtain sufficient dc voltage. If there is one shaded panel in a series connected array, it can then act as a load to the array. It may cause damage to the panel due to the heavy current passing through it in the reverse direction. To prevent this damage, bypass diodes are connected in anti parallel with each panel, and, in case of the panel being shaded current
flows through the bypass diode rather than through the panel. In series connected array, even the slightest shadow falling on a PV panel causes a significant drop in generation power. For this study, three panels connected in series have been considered. The same concept can be extended to a number of panels connected in series. Fig.2. shows that the series connection of three panels with bypass diode.

Fig.2. Schematic of Series Connected SPVA with bypass diodes

Fig.3 shows the typical V-I and P-V characteristics of three series connected panels with same illumination. The maximum power is 110.9 watts. The maximum power produced by all the panels is equal as they are equally illuminated. When they are connected in series all the panels contribute power to the load. That is the maximum possible power produced by the PV array consisting of three panels each rated at the maximum power of 37.08 watts is 110.9 watts. When these three panels are not equally illuminated the power contributed by individual panels will be different and maximum power contributed by the array will be less than 110.9 watts.

Fig.3. Simulated Characteristics of Series connected SPVA with uniform illumination

On the operation line I1 the 50% shaded panel, PV3, generates its maximum power, whereas the other two panels do not generate their maximum power yet. But all the three panels are contributing power. When the operation line moves to I2, the operation points of PV1, PV2 and PV3 move to V12, V22 and V32 respectively. The generation power of PV1 and PV2 increases. The operation point V32 of Panel-3 moves to negative voltage region because the current generated by other two panels flow through the bypass diode connected in anti-parallel with Panel-3, and the resultant power generated by PV3 becomes negative. That is PV3 cannot generate any power and causes a power loss, PV3Loss. When the operating line moves to I1, PV1 generates its maximum power, but the operating points V23 and V33 move to negative voltage region consequently cause the power loss, PV23Loss. Hence the output power on the system is decreased to

\[ PV_{total} = PV_{1output} - PV_{3Loss1} - PV_{23Loss} \]  

The generation power is following the relation \( PV_{1out} > PV_{2out} > PV_{3out} \) in this case. The total P-V characteristic of the series connected system is shown in Fig.4.b. [13]

Fig. 4.a and 4.b show the electrical characteristics of SPVA with bypass diodes with G1=100%, G2=70%, and G3=50%. The results of the Fig.4.a and Fig.4.b. are consolidated in Table-1. Though the maximum power goes up to 58.2 watts, the bypass diodes introduce multiple peaks in the characteristics.
Fig.4.a. Simulated I-V characteristics of three series connected panels under partial shading

Fig.4.b. Simulated P-V characteristics of three series connected panels under partial shading

TABLE 1
CONSOLIDATED RESULTS FOR A PARTICULAR SHADING PATTERN; G1=100%, G2=70% & G3=50%

<table>
<thead>
<tr>
<th>Panel</th>
<th>Maximum Power</th>
<th>Total Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pmax1 = 37.02 W</td>
<td>(Pmax1 + Pmax2 + Pmax3) = 76.52 W</td>
</tr>
<tr>
<td>2</td>
<td>Pmax2 = 23.89 W</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Pmax3 = 15.61 W</td>
<td></td>
</tr>
</tbody>
</table>

Total power produced by series connected panels without bypass diode = 46.45 W
Total power produced by series connected panels with bypass diode = 58.24 W

Fig.5.a. Simulated V-P curves for five different shading patterns

Fig.5.b. Simulated V-P curves for other five different shading patterns

IV. MODEL VALIDATION USING ELECTRONIC LOAD

For this study Solkar panel 3712/0507-Monocrystalline type that consists of 36 cells in series is used. Ratings of the panels used in this experiment are Pmax = 37.08 W, Imp = 2.25A, Vmp = 16.56V, Voc = 21.24V and Isc=2.55A at an insolation level of 1000 W/m² and 25°C. The shading effect is artificially generated by tilting the panels at different angles. The three series connected panels in SPVA are tilted such that they receive insolation levels of G1=100%, G2=70% & G3=50% respectively. The insolation level is measured with reference to short circuit current, that is for G=100%, the reference short circuit current is 2.55 A. The Solar panel is tilted till the required insolation level is obtained by measuring the value of Isc. Fig.6. shows the practical validation of the simulation model for the above said shading pattern using electronic load [13]-[14].
V. CONCLUSION

This paper has discussed the development of mathematical model for partial shaded SPVA using MATLAB. The model is tuned such that it is fitted with important points of practical curves. In a SPVA non-uniform insolation can damage poorly illuminated cells. A large proportion of electrical power generated by highly illuminated cells is wasted as heat in poorly illuminated cells. Use of bypass diodes can save the energy available to the load. P-V characteristics under non-uniform insolation with bypass diodes contain multiple peaks. The magnitude of the global maxima is dependent on the array configuration and shading patterns. It is demonstrated that, if the likely shading pattern on the PV array is known, the simulation model is handy to design the most optimum configuration of the PV array to extract the maximum power. As the developed model is based on the equations that take care about the model parameter variations with respect to environmental conditions, it can be used readily to predetermine the behavior of any SPV array having different number of cells in series and parallel, different number of bypass diodes and shadow conditions.

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REFERENCES


BIOGRAPHIES

Dr. B. L. Mathur is a Professor in SSN College of Engineering, Chennai. His Ph.D. work was awarded Sir Vitthal N. Chandavarkar Memorial Gold Medal on Ph.D. thesis adjudged to be the best for application to industries in the year 1979 at I.I.Sc. Bangalore. He has published around 90 papers in referred journals and international conferences. He has 42 years of teaching and R&D experience. His area of interest includes Power systems, Power Electronics & Renewable energy sources.

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