Modeling of Partially Shaded Practical Photovoltaic System Configuration

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***Abstract*—The energy supplied by the PV modules to the system is subject to variations depending onthe operating conditions, especially the irradiance and temperature values. The partial shading of the PV modules has the tremendous impact on the power output of a PV system. This paper presents the modeling and simulation of the photovoltaic (PV) systems using MATLAB models and study of effects of partial shading on the practical interconnection configurations and validates the findings from the study and PSPICE models.**

***IndexTerms*—Photovoltaic system, parallel configuration, series configuration.**

I. INTRODUCTION

The PV system presents a non-linear P-V and I-V characteristic which is strongly dependent on the environmental conditions. The fluctuating nature of the irradiation and the temperature are the main factors which determine the output characteristic of the solar PV system. Thus in addition to a study of PV output characteristics under uniform conditions, a study in partial shading conditions is also essential. Further variations in the system parameters such as parasitic parallel and series resistances also affect the fill factor and in-turn affects the PV characteristics. A dependable model so developed will facilitate the further study of maximum power point tracking methods and dynamic performance of converters easier.

II. MODELING OF PV SYSTEM

A multidimensional PV system consists of a number of PV arrays, each of which is controlled by individual DC/DC converter. Each array is made of PV modules which in-turn are a combination of series and parallel connected solar cells. A solar cell is represented by two diode model of a solar cell, the current produced by which is given by [1]:

$$I = I_{ph} – I_{o1} (e^{qV/kT} – 1) – I_{o2} (e^{qV/2kT} – 1) \qquad (1)$$

whereI_{ph} is the solar generated current, I_{o1} is the dark saturation current due to recombination in the quasi-neutral regions and I_{o2} is the dark saturation current due to recombination in the space-charge region. From a circuit perspective, it is apparent that a solar cell can be modeled by an ideal current source I_{ph} in parallel with two diodes – one with an ideality factor of 1 and the other with an ideality factor of 2.For simplicity a single diode model with diode ideality factor between 1 and 2 is considered for further modeling and simulations. The single diode model of a solar PV module is as given in Fig.1. Also parasitic resistances R_s and $R_p$as shown in Fig.1 depict the non-ideal conditions. [2]

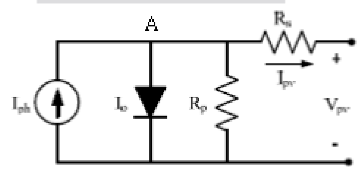


Figure 1. Equivalent circuit of a PV system

The modeling equations [2] can be derived using Kirchhoff's law on the node A

$$I_{pv} = I_{ph} - I_o \qquad (2)$$

where I_o is the diode current, I_{pv} is the PV output current.

The solar generated current $I_{ph}$is affected by solar irradiance and temperature and given by

$$I_{ph}(G)=\left(I_{sc}+K_i T_{dif}\right)\frac{G}{G_r} \quad (3)$$

where K_i is the temperature coefficient, T_{dif} is the deviation of the operating temperature from the reference temperature ($T_k - T_r$) and G and G_r are the operating and reference irradiances respectively. Thus we see the strong dependence of solar generated current on ambient temperature and solar irradiance. The diode current with a saturation current, I_{o1} is given by the Schockley Equation as:

$$I_o = I_{o1}\left[\exp\left(\frac{q(V_{pv}+I_{pv}R_s)}{AK_bT_k}\right)-1\right] \quad (4)$$

where I_{o1} varies in accordance with temperature and is given as:

$$I_{o1} = I_{rs}\left(\frac{T_k}{T_r}\right)^3 \exp\left[\frac{qE_{go}}{AK_b}\left(\frac{T_{dif}}{T_rT_k}\right)\right] \quad (5)$$

where Ego refers to the band gap energy of Si semiconductor (between 1.1 and 1.2 eV).

Considering the effect of the series and parallel resistances, $R_s$and R_p, the PV cell's output current is written as:

$$I_{pv} = I_{ph} - I_{o1}\left[\exp\left(\frac{q(V_{pv}+I_{pv}R_s)}{AKT_k}\right)-1\right] - \frac{(V_{pv}+I_{pv}R_s)}{R_p} \quad (6)$$

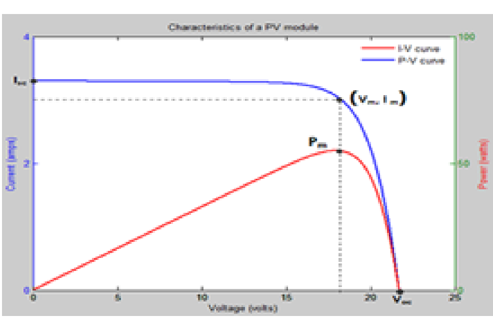
The overall capability of the PV system should be enhanced by connecting the cells either in series or in parallel, in which case, all the cells in the PV module, Ns being their given number, would contribute to the output power. The output of the module is given as:

$$I_{pv} = I_{ph} - I_{o1}\left[\exp\left(\frac{q(V_{pv}+I_{pv}R_s)}{N_sAKT_k}\right)-1\right] - \frac{(V_{pv}+I_{pv}R_sN_s)}{R_pN_s} \quad (7)$$

Since I_{pv}exists on both side of the equation, Newton's Method is used to successively update the $I_{pv}$with changing conditions. The equations (2)-(7) are used to model a PV array consisting of 2 modules each made of 36 solar cells, to obtain the I-V (P-V) characteristics of the PV array based on the flowchart shown below using MATLAB™ as a tool.Typically PV arrays comprise of several such solar cells that are interconnected in one of the following forms to attain realizable levels of output voltage and current:purely parallel connection, purely series connection, parallel-series interconnections [5].

Thefig.(2) shows the output characteristics of a PV module as per the below specification.

PV module specifications: Pmax= 55.03 W, Vmp = 17.97 V, Isc = 3.301 A, Voc = 21.71 V, Imp = 3.062 A, Ta = 298 K, No. of cells = 36, G = 1000 W/m^2



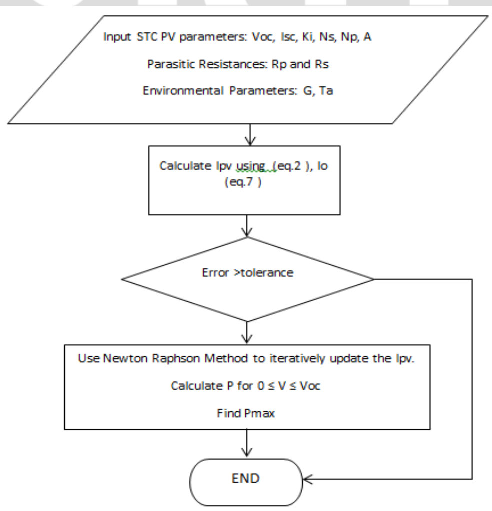


Figure 2.I-V and P-V output characteristicsFigure 3. Flow chart for modeling the PV system

III. PARTIAL SHADING CONDITION AND ITS EFFECTS

Performance of a PV system is dependent on temperature, array configuration, solar insolation, and shading across it [6]. Shading can occur when the PV arrays/modules get covered by shadows of passing clouds, buildings, etc., or even by shadows cast by other modules/arrays. As a result the ideal operation of the PV systems is severely affected with deterioration in P-V and I-V characteristics.Shading in solar cells is critical issue in their performance because

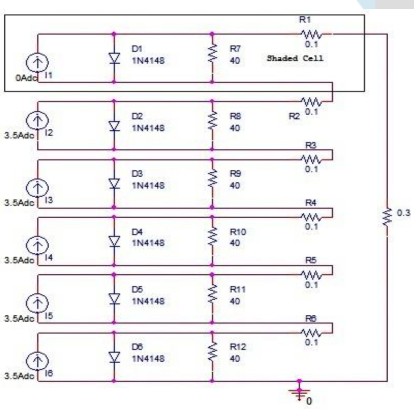
a. As the shaded cells can get reverse biased they consume power instead of generating power resulting in loss of total output power.
b. The power losses in the individual shaded cells result in local heating and increase the temperature affecting surrounding cells which creates thermal stress on the entire module and cause hot spots and local defects which potentially results in the failure of the entire array [7].
c. Under extreme cases of shading the reverse bias on the solar cell might exceed its breakdown voltage causing damage, cracks and an open circuit at the serial branch where the cell is connected [8].

IV. MODELING OF PARTIAL SHADING CONDITION

Shading has been implemented across a single cell by using the DC point analysis in PSPICE. The photo current across one cell has been varied and the changes in the output voltage, output current, and power has been tabulated. The change in irradiation and temperature is modeled as a change in I_{sc}as per equation (3) and is shown in fig. (2)-(3) for series and parallel configuration. Six different scenarios with shading ranging from 0% to 100% (0-3.5A) in steps of 20% have been studied and readings have been included in Table.1 and Table.2 for two different configurations.

Series Connected Cells

Figure3 shows six solar cells connected in Series with shading ranging from no illumination to full illuminationacross the first cell. When the cell gets shaded, the photonic current is reduced. As a result the current that was previously flowing through the diode is also reduced. This allows less current to flow through the output.
In order to maintain the same output current across each cell (since the cells are in series), the shaded cell operates under reverse bias and negative voltages are generated across the output voltage as indicated in Table.1. This effect becomes more prevalent as the percentage of shading across the cell under consideration is increased. The deterioration of power from full illumination across all the cells to full illumination across five cells and 100% shading across the first cell is 99.26% for the given load.



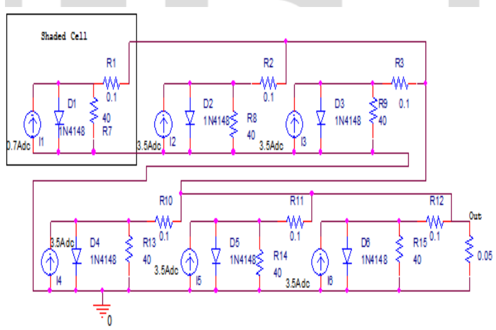


Figure 2. Series ConfigurationFigure 3. Parallel Configuration

Parallel Connected Cells

Figure 4.shows six solar cells connected in Parallel with shading ranging from No illumination to Full illumination across the first cell. Under uniform full illumination across each cell, portion of the photonic current flows through the diode and maintains the required voltage to produce an output current. All these individual currents add up to give the final current while voltage across eachcell remains constant. When one of the cells gets shaded, the amount of voltage at the diode required to produce the same output current is reduced. But in case of parallel cells this effect is very small. As the shading is increased, the photonic current of the shadeddiode may not be enough to forward bias its diode. However, this is made up by portions of photonic current from the five illuminated

Table 1. Total Output Power under Varying shadingconditions for Six Series connected cells

Iph of Shaded Cell (A)	Voltage across shaded cell (V)	Voltage across non-shaded cells (V)	Vout (V)	Iout (A)	Pout (W)
3.5	0.1744	0.1744	1.046	3.487	3.647
1.4	-7.67	1.631	0.4764	1.588	0.756
0.7	-9.84	2.025	0.283	0.944	0.267
0	-12	2.42	0.09	0.299	0.0268

Table 2. Total Output Power under Varying shadingconditions for Six Series connected cells

Iph of Shaded Cell (A)	Current through shaded cell (A)	Current through non -shaded Cells (A)	Iout(A)	Vout(V)	Pout(W)
3.5	2.832	2.832	17	0.85	14.44
1.4	1.127	2.962	15.75	0.787	12.41
0.7	0.54	2.95	15.329	0.766	11.75
0	0.696	2.99	14.884	0.744	11.08

cells as they are connected in parallel. Thus the output voltage is still maintained constant but at a slightly lower value. However the total output current reduces resulting in reduced output power.

V. CONCLUSION

A PV system for the given specification has been modeled. This model can be extended to any specification using similar approach. Simple and accurate models of solar cells under different shading patterns have been modeled in PSPICE for two different array configurations. The same model can be extended to a larger array used in the practical solar PV systems. The model presented also show that the output power in both the configurations is affected by the partial shading condition but it is more profound in the series connected solar PV array configuration. Since most practically used solar modules in market are made of series connected cells, MPPT for partial shading conditions becomes essential.

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