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Generalized Algorithm for Modelling of SPV Array under Non-uniform Insolation

Engineering

KEYWORDS: SPV array, Non-uniform insolations, generalized algorithm.

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ABSTRACT

A generalized algorithm for determining the I-V and P-V characteristics of solar photovoltaic (SPV) array, under uniform and non-uniform insolation conditions is proposed in this paper. The algorithm is capable of developing the characteristics of SPV array of any configuration with any kind of shadow pattern. Individual module specifications are also inputted. A MATLAB code is developed for the algorithm and I-V and P-V characteristics of sample system of [3*3] array are identified for ten shadow patterns. For each shadow pattern values of Vmp and Imp (voltage and current at maximum power) are also identified using the algorithm, which are required for maximum power point tracking (MPPT).

I.INTRODUCTION

Solar photovoltaic (SPV) system has negligible operating cost but has high initial capital cost. In order to recover the high initial capital cost of SPV system efficient utilization of the installed SPV system is necessary. Therefore maximum available electrical power needs to be drawn from a given SPV installation under all situations. The output power of a SPV array decreases considerably, as current-voltage (I-V) curves of different solar cells or modules are not identical due to non-uniform insolations. Before attempting to minimize or avoid the mismatch effects, a thorough understanding of their inception and behavior is required. Since the field testing is quite costly as well as time consuming and depends largely on the prevailing weather condition, it is very necessary to define a circuit based modeling and simulation which properly allows including the effect of mismatch with high accuracy. Computer simulation is a most valuable tool since makes it possible to predict a large variability of situations in the performance of a system.

In recent some years, the effect of partial shadowing on the SPV energy yield of solar systems has been discussed widely in literature. Villalva M. G., et.al [1] have proposed a method of modelling and simulation of photovoltaic arrays, to find the parameters of the nonlinear I–V equation by adjusting the curve at three points: open circuit voltage (Voc), maximum power (Pmp), and short circuit current (Isc). Chris Deline, et.al [2] have presented a novel analytical approximation of the effect of inter-row shading on large photovoltaic (PV) arrays. Many researchers [3-7] presented software modelling and simulation of solar photovoltaic array under non-uniform insolation conditions. Chowdhury, et.al [8] have presented modelling, simulation and performance analysis of a PV array in an embedded environment. Gow and Manning [9] have developed of a suitable model of photovoltaic array for the use in power-electronics simulation studies so here solar array is integrated with various power electronic circuits in order to harvest the electrical energy from it. Still no one has proposed a generalized algorithm suitable for determining current-voltage (I-V) and power voltage (P-V) characteristics of SPV array under uniform as well as non-uniform insolation conditions.

An attempt has been made in this paper, to develop a generalized algorithm suitable for developing the I-V and P-V characteristics of the SPV array of any viable configuration under uniform and non-uniform insolation due to partial shadow.

II. ELECTRICAL REPRESENTATION OF A PRACTICAL SPV MODULE

When light (photons) falls upon the solar cell, electrons are knocked loose from the atoms of the semiconductor material creating the electron-hole pairs. If electrical conductors are attached to the positive and negative sides, forming a closed electric circuit, the electrons are captured in the form of photon current, Iph. Hence the photovoltaic cell is a semiconductor device which behaves as a current source when driven by a flux of solar radiation from the sun.

During darkness, the SPV cell is not an active device; it works like a diode (p-n junction). However if it is connected to an external supply voltage, it generates a current called reverse saturation current or diode current, ID. This current is represented by Shockley equation as given by eq. (1).

$$I_D = I_r\left[\exp\left\{\frac{V_D}{V_t}\right\} - 1\right] \quad (1)$$

Where, V_D=Diode (D) Voltage ,

$$V_t = \frac{nkT}{q} = \text{Thermal voltage}$$

Where, k is Boltzmann constant= 1.38×10−23 J/K , q=1.6×10-19C , n=Ideality Factor and T is absolute temperature of solar cell in Kelvin. Ir - Reverse saturation current of the cell. The photon generated current (Iph) in the solar cell that results from solar radiation flows in the direction opposite of the dark saturation current. Its value remains the same regardless of the external supply voltage and therefore it can be measured by the short circuit current of the cell (Isc=Iph). This current is directly proportional to the intensity of solar radiation as increased radiation is able to separate more charge carriers.

$$I_{pv} = I_{ph} - I_D \quad (2)$$

Practical modules/arrays are composed of several SPV cells connected in series and parallel and the observation of characteristics at the terminals of the solar cells/module/array requires the additional parameters to be introduced in the basic Rauschenbach equation [10]. That is, to include the effect of leakage current and conductive losses of the cell, Rsh and Rse are added in the equivalent circuit. Where Rsh is the equivalent shunt resistance and Rse is equivalent series resistance. The final electrical equivalent circuit of the solar cell consists of a current source (Iph) and a diode (D) plus series and parallel resistances (Rse and Rsh) as shown in Fig.1.

Fig.1: Electrical equivalent circuit of five-parameter model of Practical SPV cell

This is known as standard five-parameter model or single-diode model of the solar cell [7]. From Fig.1, the mathematical equation of the output current (Ipv) of the cell is written as given by eq. (3).

$$I_{PV} = I_{ph} - I_D - I_{sh} \quad (3)$$

$$I_{PV} = I_{ph} - I_r\left[\exp\left\{\frac{V_{PV} + I_{PV}R_{se}}{V_t}\right\} - 1\right] - \frac{(V_{PV} + I_{PV}R_{se})}{R_{sh}} \quad (4)$$

The eq. (4) represents a practical solar cell. Here the five parameters are Iph, Ir, Vt, Rse and Rsh. This equation can also be used to represent a series/parallel connected cells/module by suitably modifying its parameters as shown in Table 1.

Table 1: Modification **of Parameters SPV module/array from SPV cell/module**

Parameters of SPV cell	Parameters of Series SPV string of N_s cells	Parameters of Parallel array of N_p cells
I_{ph}	I_{ph}	N_pI_{ph}
I_r	I_r	N_pI_r
V_t	N_sV_t	V_t
R_{se}	N_sR_{se}	R_{se}/N_p
R_{sh}	N_sR_{sh}	R_{sh}/N_p

As with the connection of the cells to form the modules, a number of modules can be connected in a series string to increase the voltage level, in parallel to increase the current level or in a combination of the two. Here in the table 1, Ns is no. of solar cells/modules connected in series and Np is no. of cells/modules connected in parallel. The exact configuration depends on the voltage and current requirements of the load. Matching of the interconnected modules in respect of their outputs can maximize the conversion efficiency of the solar array.

Eq. (4) represents the five-parameter model of one-diode equivalent model of solar cell. Few authors have proposed various different models that present better accuracy and serve for different purposes in solar photo-voltaic. A three-diode model [11] is proposed to include the influence of the some effects that are not taken care by the previous models.

For simplicity and sensibly good accuracy for the work presented a single-diode five-parameter model of Fig. 1 is considered. This model offers a good conciliation between simplicity and accuracy and has been used by few other investigators, sometimes with simplifications but always with the same basic structure. The unfussiness of the single-diode model with the method to adjust the parameters, make this model perfect for power electronics designers who are looking for a simple and effectual model for the simulation of solar devices with power converters. For the work presented in the paper the single diode five-parameter mathematical model of a practical SPV module has been simulated in MATLAB.

III. BASIC CONNECTION METHODS OF SPV ARRAY AND RELATED PROBLEMS

A number of SPV modules are connected in series string to approach to requisite voltage level and in parallel to get the requisite current level or in a combination of the both. The exact configuration of SPV array depends on the current and voltage requirements of the load. Mismatching of the interconnected modules in respect of their outputs can decrease the conversion efficiency of the array considerably. In the SPV power generation system, multiple solar PV modules are generally connected in series in order to obtain required dc voltage. If there is any one shaded module in a series-connected array, it can then proceed as a load to the array. It may lead to damage of the module due to the heavy current passing through it. To avoid this damage, bypass-diodes are connected in anti-parallel with each module, and, in case of the modules are shaded; the current may pass through the bypass-diode rather than through the module. In series connected array, even the smallest amount shadow falling on a solar PV module causes a considerable drop in generated electrical power.

When the illuminated solar PV modules and the non-illuminated solar PV modules are connected in parallel, the generation voltage is fixed for each solar PV module and is consistent throughout the entire SPV generation system, and the current generated from each solar PV module flows without constraint.

In distinction, when each PV module is connected in series, the same current flows through each module and the output voltage becomes the addition of the voltages across each of the modules. However, the voltage of each module is decided according to the generated PV current, which depends on the illumination/shaded conditions. Therefore, the most advantageous generation voltages are not always obtained for every solar PV module. In particular, when some of the solar PV modules do not have satisfactory generation current, the voltage of the SPV modules is significantly decreased and the resulting generation power is also significantly decreased. The performance analysis for series and parallel connected solar PV modules is analyzed in the subsequent sections through reflection of the operating point.

IV. BASIC SPV ARRAY CONFIGURATIONS UNDER NON-UNIFORM INSOLATION CONDITIONS

Under non-uniform insolation, performance of solar PV modules in series and then parallel is to be be investigated and discussed in this section.

IV (A). OPERATION OF SERIES-CONNECTED SOLAR PV MODULES

Fig. 3 shows the connection diagram of three-modules connected in series, where each module receives different insolation. The shaded conditions (100%, 75% and 25%) for PV modules have been considered.

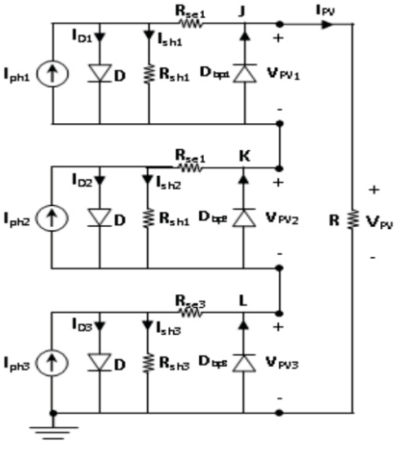
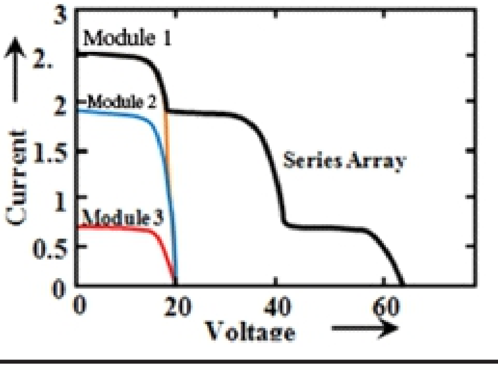


Fig.3: Series Connected Solar PV Array with Bypass-Diodes

The bypass-diodes are connected in array then the reverse current Ipv-Iph3 will flow through the bypass-diode Dbp3 and the module will be saved from the damage. A portion of power from high insolation modules, instead of getting wasted in low-insolation modules will be available to the load. Low insolation modules however make no contribution to the load power as these are short-circuited by the bypass-diodes. Electrical characteristics of the solar PV array having three solar PV modules in series with different insolation with bypass diode are shown in Fig. 3. [12]

In series connection, array characteristics can be obtained by adding the voltage of each module at every current. In case the array current exceed the short circuit current of a particular module, the voltage of that module will be -0.7 V (the forward cut-in (knee) voltage of the bypass diode). I-V characteristics of the array for three non-uniformly illuminated series connected modules plotted in this manner is depicted in Fig. 4(a). P-V characteristic of this array is also derived from I-V characteristic of Fig. 4(a) and same is shown in Fig. 4(b) [12].



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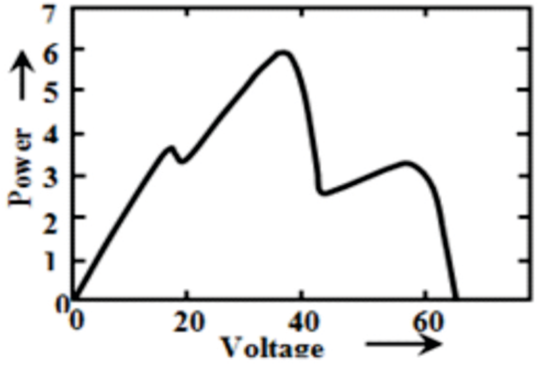


Fig.4: Characteristics of Three-Series connected modules under Partial Shading

IV(B) OPERATION OF PARALLEL-CONNECTED SOLAR PV MODULES

Fig.5 shows the equivalent circuit of solar PV array consisting of three parallel connected modules where each module receives different insolation (G). For example Module-1 receives 100% insolation, Module-2 receives 75% insolation and Module-3 receives 25% insolation. The I-V and P-V characteristics of three-parallel connected modules under partial shading with similar Voc (as Voc negligibly depends upon the insolation G) are shown in Fig.6 (a) and (b) respectively.

The characteristics shown in Fig.6 disclose that both the shaded and non-shaded modules can operate in the area where each module can supply power. So, the total output power characteristics of these modules are obtained as shown in Fig.6(a) and (b).

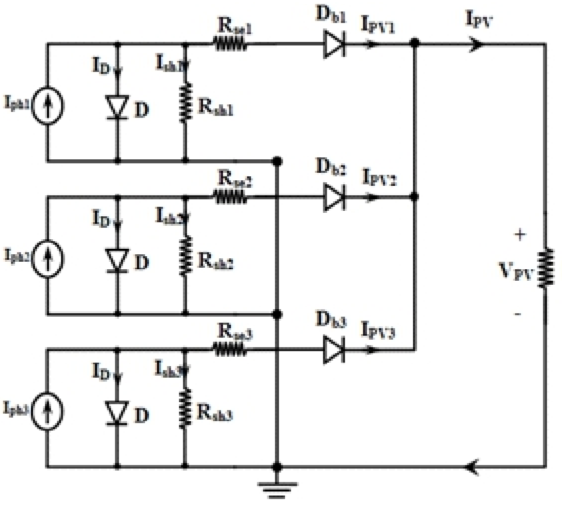
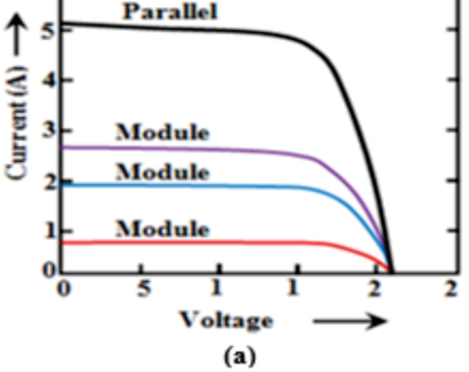
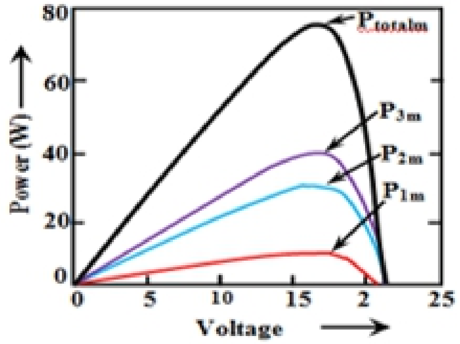


Fig.5: Parallel Connected SPVA with blocking diodes



(a)



(b)

Fig.6 (a),(b): I-V and P-V Characteristics of three-parallel connected modules under partial shading

The **total output power is given by eq.(5).**

$$P_{total} = P_{1out} + P_{2out} + P_{3out} \tag{5}$$

If the voltage of all the three-modules is equal at the maximum power point, then the total maximum power is given by eq. (6)

$$P_{totalmax} = P_{1max} + P_{2max} + P_{3max} \tag{6}$$

V. GENERALIZED ALGORITHM FOR SIMULATION OF SPV ARRAY UNDER PARTIAL SHADOW

For modeling of practical SPV array under partial shadow, a generalized algorithm is proposed here. This algorithm is applicable for SPV array of any viable configuration and the specification of individual module can also be used as per the needs. The insolation and temperature are fed individually for the module, hence different of shadow pattern (sample shadow patterns are shown in table 3) can be inputted and its corresponding I-V characteristics can be drawn quickly here.

The steps to be followed in the proposed algorithm are as follows:

Step 1: Read size of SPV array (Ns, Np), insolation (G) temperature (T) and Module Specifications at standard test conditions (STC).

Input the no. of modules connected in series in a string (Ns), no. of strings connected in parallel (Np) and complete insolation pattern (in W/m2) and temperature (in Celcius) over the solar array.

$$G=\begin{bmatrix} G_{11} & \cdots & G_{1Ns} \\ \vdots & \ddots & \vdots \\ G_{Np1} & \cdots & G_{NpNs} \end{bmatrix},\ T=\begin{bmatrix} T_{11} & \cdots & T_{1Ns} \\ \vdots & \ddots & \vdots \\ T_{Np1} & \cdots & T_{NpNs} \end{bmatrix}.$$

Step 2: Compute module voltage and current as per insolation (G) and temperature (T) inputted

For each module connected in series, calculate voltage (V_{pv}) produced across individual module for given current (I_{pv}) at specified insolation (G) and temperature (T) by the following equation

$$I_{PV} = I_{ph} - I_r\left[\exp\left\{\frac{V_{PV} + I_{PV}R_{se}}{V_t}\right\} - 1\right] - \frac{(V_{PV} + I_{PV}R_{se})}{R_{sh}} \tag{7}$$

Step 3: Extrapolation of Module Specifications at specified G and T

Module specifications at STC are inputted in step 1 and now these specifications are extrapolated at specified G and T by the following equations:

$$I_{sc} = \{I_{scref}[1 + \alpha(T - T_{ref})]\}\frac{G}{G_{ref}} \tag{8}$$

$V_{oc}=V_{ocref}*(1+\beta(T_{actual}-T_{ref}))$ (9)

$I_{mp}=I_{mpref}*(G/G_{ref})$ (10)

$V_{mp}=V_{mpref}*(1+\beta(T_{actual}-T_{ref}))$ (11)

$V_t=V_{tref}*(T_{actual}/T_{ref})$ (12)

Step 4: Compute String Voltage and Current

Calculate total string voltage ($V_{pvtotal}$) at all possible string currents (I_{pv}) for N_p strings: Repeat step 2 for N_s times to determine total string voltage (V_{pv}) by eq.(7) at specified current (I_{pv}):

$$V_{pvtotal}=V_{pv1}+V_{pv2+\ldots}\ V_{pv\,Ns} \qquad (13)$$

Step 5: Compute String Current for an Array Voltage

Calculate the total string current ($I_{pvtotal}$) for the specified array voltage (V_{pv}): Increment the array voltage (V_{pv}) in steps and calculated individual string current (I_{pv}) by interpolation in the I-V relation, obtained in step 3, calculates the total string current and total power (P_{pv}) as follows:

$$I_{pvtotal}=I_{pv1}+I_{pv2}+\ldots\ I_{pv\,Np.} \qquad (14)$$

$$P_{pvtotal}=(V_{pvtotal})*(I_{pvtotal}) \qquad (15)$$

Step 6: Plot I-V and P-V characteristics of solar array

Plot I-V ($I_{pvtotal}$-$V_{pvtotal}$) and P-V ($P_{pvtotal}$-$V_{pvtotal}$) characteristics of complete solar array.

VI. SYSTEM INVESTIGATED

To examine effectiveness of the proposed algorithm, [3*3] sized SPV array is considered shown in Fig.7 and data inputted to the array is presented in table 3. The insolation over individual module is inputted as Gij, where i represent module no. in a string and j represent string no. in SPV array. A MATLAB program is developed as per the proposed algorithm. The program is executed for different insolation pattern as given in table 3.

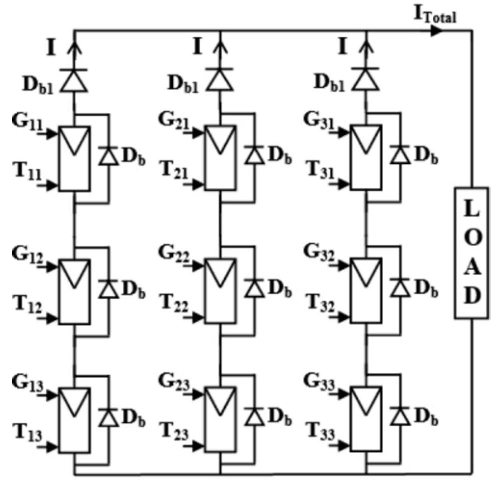


Fig.7: Configuration of Simulated SPV Array [3*3]

Table2: Datasheet Values of a Practical SPV Module

Datasheet value at STC			
I_{sc}	2.55A	I_o	108μA
V_{oc}	21V	R_{se}	3.407Ω
V_{mpp}	16.8V	R_{sh}	27.076Ω
I_{mpp}	2.2A	n_s	36

VII. SIMULATED SPV ARRAY AND ITS I-V AND P-V CHARACTERISTICS

The MATLAB program is executed for different insolation pattern (Table 3) and it provides I-V and P-V characteristics as well as corresponding values of V_{mp}, I_{mp} and P_{mp}. In Fig. 8(a) and (b) I_1, I_2 and I_3 are currents of individual SPV string and I_{total} are the total current of SPV array: P_1, P_2 and P_3 are electrical powers available of individual SPV string and P_{total} is the total electrical power available at SPV array.

Table 3: Various Insolation Patterns for SPV array of [3*3]

Shade Pattern	Insolation Pattern	V_{mp}(V)	I_{mp}(A)	P_{mp}(W)
1	$G_{11}=G_{12}=G_{13}=0.9Sun, G_{21}=G_{22}=G_{23}=0.7Sun, G_{31}=G_{32}=G_{33}=0.4Sun$	39.42	3.91	154.21
2	$G_{11}=G_{21}=G_{31}=1Sun, G_{12}=G_{22}=G_{32}=0.8Sun, G_{13}=G_{23}=G_{33}=0.5Sun$	24.58	6.14	151.01
3	$G_{11}=G_{12}=G_{13}=1Sun$ $G_{21}=G_{23}=G_{31}=G_{32}=G_{33}=1Sun, G_{22}=0.5Sun$	28.69	7.49	215.13
4	$G_{11}=G_{12}=G_{13}=G_{21}=1 Sun, G_{22}=G_{23}=G_{31}=G_{32}=G_{33}=0.5Sun$	28.52	5.70	162.58
5	$G_{11}=G_{12}=G_{13}=1Sun$ $G_{21}=G_{22}=G_{23}=1Sun$ $G_{31}=G_{32}=G_{33}=0.4Sun$	38.24	5.41	206.93
6	$G_{11}=G_{12}=G_{13}= G_{21=}1Sun, G_{22}=G_{23}=G_{31}=G_{32}=G_{33}=0.5Sun$	37.18	4.19	156.09
7	$G_{11}=G_{12}=G_{13}=0.4Sun$ $G_{21}=G_{22}=G_{23}=0.6Sun$ $G_{31}=G_{32}=G_{33}=0.8 Sun$	34.1	4.55	155.38
8	$G_{11}=G_{12}=G_{13}=1Sun$ $G_{21}=G_{22}=G_{23}=0.8Sun$ $G_{31}=G_{32}=G_{33}=0.5Sun$	36.74	5.85	215.13
9	$G_{11}=G_{12}=G_{13}=0.5Sun$ $G_{21}=G_{22}=G_{23}=0.5Sun$ $G_{31}=G_{32}=G_{33}=0.8Sun$	37.45	3.19	119.60
10	$G_{11}=G_{12}=G_{13}=1Sun$ $G_{21}=G_{22}=G_{23}=1Sun$ $G_{31}=G_{32}=G_{33}=1Sun$	49.45	6.66	329.16

The table3 shows the various insolation patterns inputted to the SPV array of (3*3) and its corresponding maximum power (P_{mp}) and voltage and current of maximum power (V_{mp}, I_{mp}) are also shown in same table.

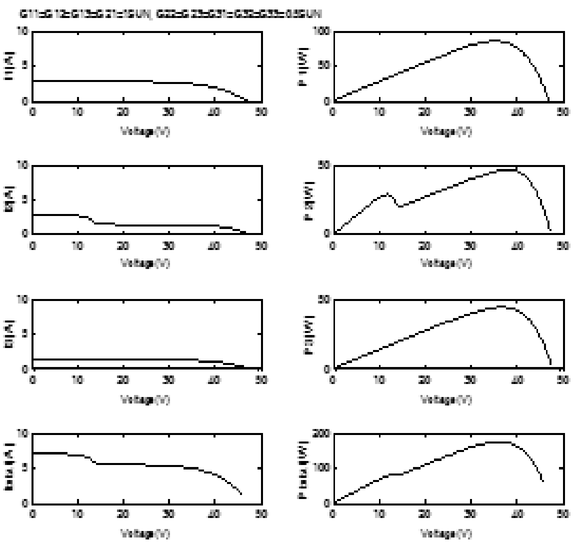


Fig.8 (a): I-V and P-V characteristic of individual string and Total SPV array for insolation Pattern 4

In Fig.8(a) two steps are observed in I-V characteristics whereas in Fig.8(b) three steps are observed in I-V characteristics of SPV array. The inputted insolation pattern in Fig.8(a) is having two levels whereas in Fig.8(b) the insolation pattern is having three levels.

It may observed here that under non-uniform insolation the I-V characteristics have multiple steps and this no. of steps in the I-V characteristics is equal to no. of levels in the inputted insolation over

SPV array. Further it is also observed in the same figures that the no. of steps in I-V characteristics is equal to no. of maximas in P-V characteristic of the SPV array. Therefore it is inferred that no. of maximas in P-V characteristics are equal to no. of different levels in the insolation over SPV string in SPV array.

VIII. CONCLUSIONS

A single diode, five-parameter mathematical model of a practical SPV module has been simulated in MATLAB. A new generalized algorithm for modeling of practical SPV array under non-uniform insolation (shaded) conditions, with different SPV array configurations, has been proposed in this paper. Investigation reveals that current-voltage (I-V) curves under unequal insolation (partial shadow) conditions have multiple steps, while the P-V curves have multiple peaks. Maximum number of peaks on P-V curve may be at most equal to the number of modules connected in series (Ns). Results also showed that in addition to insolation and temperature, the magnitude of global MPP, and the voltage at which it occurs are also dependent on shading pattern as well as solar array configuration.

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