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DOI
10.1109/PEDSTC49159.2020.9088407

Publication date
2020

Document Version
Final published version

Published in
2020 11th Power Electronics, Drive Systems, and Technologies Conference, PEDSTC 2020

Modeling and estimation of the maximum power of solar arrays under partial shading conditions

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***Abstract*— Prediction of output power has become important with the expansion of photovoltaic systems in recent years. Power prediction can be used for economic analysis, loss calculation and optimal designs. In this paper, a new approach for estimating the maximum output power of a photovoltaic power plant is proposed using the meteorological data under cloudy conditions. Basic concepts for understanding the behavior of modules in partial shading condition (PSC) are presented. To find the global maximum power point (GMPP), the shading index is introduced which can be used to find the maximum power point using the climate data. Then, analytical approach has been employed to find voltage and current of arrays at GMPP for both series and series-parallel configurations. The analytical approach is verified using MATLAB-SIMULINK software. Various experimental tests are made to confirm the aforementioned method validity.**

Keywords— Photovoltaic, partial shading, array mismatch, power estimation, modeling

I. INTRODUCTION

Due to environmental issues and limited fossil resources, the use of renewable energies, especially solar energy, is inevitable. Hence, the photovoltaic installation has grown so fast in the last decade [1]. However, one of the main factors that greatly affects the output power of the photovoltaic plant is shading. Shading is caused by obstacles such as trees, buildings, clouds and etc. This factor not only affects the electrical characteristic of shaded modules but also affects the modules that are in uniform irradiance in series of shaded modules [2]. This is due to the mismatch between the electrical characteristics of modules [3]. This phenomenon, which is known as partial shading effects, reduces the output energy yield of arrays. In addition, it may causes hot-spot phenomena [4]. Therefore, anti-parallel diodes are added to prevent the module damage. When series modules receive uneven radiation, the anti-parallel diodes avoid hot spots by creating another electrical path for currents [5]. This solution, however, has two adverse effects. First, different power peaks are appeared in the array I-V curve, and the optimal MPP may not tracked. Second, finding the global maximum power point will be complicated due to multiple power peaks [6]. Accordingly, conventional MPPT methods are not able to find GMPPT in this situation. Different approaches have been made to finds GMPPT. some methods have been reviewed in [7] to solve the problem. To model the arrays and calculate the GMPPT under non-uniform irradiance conditions, nonlinear equations must be solved. Solving these equations is complicated due to the nonlinear I-V characteristics of arrays. In [8] Lambert function has been proposed to solves the equations. The Lambert function is used to solve exponential nonlinear equations [8]. Then, the simplified equations by Lambert function, are solved by numerical analysis methods, this approach is complex and time consuming, and has convergence problem. In addition, it is incapable of finding the maximum power and does not involve diode bypass effects. It is necessary to develop a technique to find GMPP location and the amount of maximum power by the meteorological data. Therefore, this paper proposes a technique to do so. In [9], the correlation between environment variables and output power parameters has been made using statistical and mathematical equations and regression. Then, in the paper suggests a model to predict the output power. The method is not only complex but also it does not considers the effect of partial shading condition. It also has 5.4% deviation from actual value. [10] finds the maximum power by searching and comparing different points. [11] provides a simple way to find maximum power but it has an error in estimating the voltage and therefore the power. It also assumes that the location of the maximum power is known. Several papers have investigated partial shading effects to find maximum power using MATLAB-based simulation rather than mathematic modeling [12]-[13]. To overcome the previous problems, this paper purposed a new approach to model the arrays in partial shading condition to estimate the maximum power of the photovoltaic power plant. The presented method is based on the simplified electrical equation and behavior concept of the array in PSC with regard to number of shaded and non-shaded module.

The paper is organized as follows. Section II describes the PV cell modeling using single diode model. section III provides a criterion by which the location of the maximum power point is determined. Section IV presents the extracted equations to find the voltage and current of arrays at the MPP. Section V shows the simulation and practical implementation results.

II. MODELING OF PHOTOVOLTAIC ARRAY

A single diode model can be used to model the PV modules and investigate its characteristic in different conditions [14]. This model depends on the environmental and physical parameters of the PV. Fig. 1. shows the single diode model circuit. According to KVL and KCL rules, the relation of current and voltage in a module is as follows:

$$I_{pv} = I_{ph} - I_o\left[\exp(\frac{V_{pv}+R_sI_{ph}}{A})-1\right]-\left[\frac{V_{pv}+R_sI_{ph}}{R_{sh}}\right] \qquad (1)$$

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Where I_{ph}, I_{pv} and I_o are photoelectric current of PV cells, module output current and the diode reverse saturation current, respectably. R_{sh} and R_s are the shunt and series resistors, respectively. V_{pv} is the module voltage.

A=ηkT/q , where η is Boltzmann constant, q is electron charge and T is temperature.

Module current dramatically depends on the irradiance. The PV current has small dependency on temperature, which is shown by the coefficient $\alpha_{I_{sc}}$. The current relation is given below:

$$I_{ph} = \frac{G}{Gstc} I_{ph_{stc}} \times (1 + \alpha_{I_{sc}} (T - T_0)) \tag{2}$$

In (2) the temperature has small effect on the changes the current because of small value of its coefficient.

But the temperature has a significant effect on the module voltage [15]. The relation of voltage is given as:

$$V_{oc} = V_{oc_{stc}} + \beta_{V_{oc}} (T - T_0) \tag{3}$$

Where $\beta_{V_{oc}}$ is the voltage coefficient and V_{oc} is the open circuit voltage of the module.

In contrast to the current of a module, its voltage has low dependency on the irradiance level. To clarify this fact, the ideal single diode model is considered (R_s, R_{sh} are neglected), then V_{oc} is calculated from (1) as follows:

$$V_{oc} = \frac{1}{A}\left[Ln(\frac{I_{sc}}{I_o}) \right] \tag{4}$$

Assuming that irradiance changes by a factor of x, V_{oc} can be calculated from (5):

$$V_{oc,new} = \frac{1}{A}\left[Ln(\frac{xI_{sc}}{I_o}) \right] = V_{oc} + \frac{1}{A} Ln(x) \tag{5}$$

Substituting $k = 1.381 \times 10^{-23} j/k$, $q = 1.602 \times 10^{-19} c$

$T = 298^{\circ} k$ and $\eta = 1$ in equation (5):

$$V_{oc,new} = V_{oc} + 0.0257 Ln(x) \tag{6}$$

So, if the irradiance is multiplied by two (x=2), $V_{oc,new}$ changes only 18 mv. Therefore, we can neglect the effect of irradiance on the module voltage.

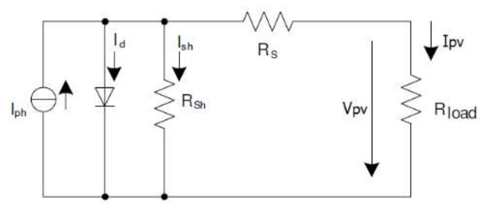

Fig. 1. Single diode model of PV module

III. Determine the Bypass Diode Operatiom to Find the Maximum Power Point

To protect the modules against the hot spot effects and to gain more power, the bypass diode should be activated in partial shading condition. The bypass diode activation depends on the number of modules which has been covered with cloud, terminal voltage of array and also radiation on PV modules [16]. So, sometimes bypass diode may be inactive while the modules are shaded because of the terminal voltage. In this circumstance, the array current is proportional to the module which has the lowest radiation. To determine when the bypass diodes should be activated and also to find the peak power of the array, an analytical equation is extracted in this section. The criterion which is used in this paper to realize the operation of bypass diode depends on the number of shaded modules and the amount of radiation which they receive. This parameter corresponds to the value of output power, so the largest value determines the maximum peak power points location. Therefore, the following two conditions are required to enable bypass diodes:

1. Modules are partially shaded and shading have a considerable effect on output power.

2. The output power is increased by activating bypass diodes.

A. Series Congiguration

A series array consists of Ns modules. Each module is equipped with an anti-parallel diode to protect and prevent the hot spot effect. So, they will be enabled just in a non-uniform radiation. In order to determine which diode is switched on, one must pay attention to the irradiance and the number of modules in the shade. For this reason the following shading index (SI) is introduced:

$$SI_i = (\frac{G_i}{G_{stc}}) \times (1 - \frac{N_j}{N_s}) \rightarrow st: 0 \le N_j < N_s \tag{7}$$

Where Gstc is the irradiance in standard test conditions (STC). According to Fig. 2, G_i is radiation on each shaded module. Nj is the number of bypass modules. Ns is the total number of modules that are in series in the array. The greatest value of SI_i determines the operation of bypass diode. To calculate SI_k , the modules with number j<k must be bypassed. If SI_k has the greatest value, then the maximum current corresponds to the maximum power is obtained as follows:

$$I_{mpp} = I_{mppt} \times (\frac{G_k}{G_{stc}}) \tag{8}$$

Where Imppt is the maximum current of module produced at STC. Impp is the maximum current of the array. It changes as the radiation changes. In this equation, the effect of temperature is neglected due to its small effect on the current. For example, as shown in Fig. 2, assuming Ns=3, and the irradiance G1=250, G2=700 and G3=950, the value of the shading index proposed in (7) will be SI1= 0.25, SI2=0.46 and SI3=0.31. In this case, since SI2 is higher than the others, modules smaller than j <2 have to be bypassed in order to extract more power in this shading pattern, that's mean, the module with the radiation of 250 (w/m^2) must bypassed. In this case, the maximum current will be $I_{MPP} \times (700/1000)$. Note that if the values of SIi are equal to each other, we choose the smallest i, so the converter will make less effort to increase the voltage needed for the inverter.

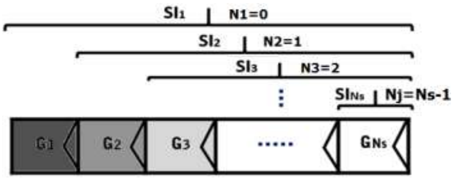

Fig. 2. PV array with different radiation on each module

B. Series-parallel Congiguration

In series-parallel configuration, to find the point at which the power is maximized, one has to calculate the average shading index for each i-th module. Then, a number closer to the unit value, or in other words, the greatest number indicates the GMPP location:

$$SI_{i,new} = \frac{1}{N_p} \sum_{k=1}^{k=N_p} (SI_i)_k \tag{9}$$

Where Np is the number of array in parallel.

For example, according to figure (3), if these two array are parallel, the value of shading index will be as follows:

$$SI_{1,new} = \frac{(SI_1)_1 + (SI_1)_2}{2} = 0.32$$
$$SI_{2,new} = \frac{(SI_2)_1 + (SI_2)_2}{2} = 0.55$$
$$SI_{3,new} = \frac{(SI_3)_1 + (SI_3)_2}{2} = 0.57$$

According to the calculated values above, the maximum power is delivered the inverter when modules with j<2 are bypassed by the anti-parallel diodes; in other words, the terminal voltage of the array is set by the converter to the point where one of the modules in each array, which limits the overall current, is bypassed. In this case, the converter will not be located at a local power point. For a better understanding the P-V characteristic of these two parallel arrays are depicted in Fig. 4. It is clear that the maximum power is at the point where only two modules per array contribute in power production and the others are bypassed. Determining GMPP location with SI has more accuracy in string-inverter than series-parallel configuration when the number of parallel arrays increases.

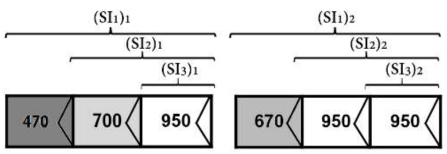

Fig. 3. Two parallel array in partial shading condition

IV. PEAK POWER CALCULATION

To find the output power, it is necessary to determine the current and voltage of arrays. In section II the current of the array was estimated by equation (8). In this paper some equations are derived for estimating array voltage in partial shading condition.

According to the V-I characteristics of the shaded modules, in a series array, the number of power peaks is equal to the number of distinct irradiances on the modules [17].

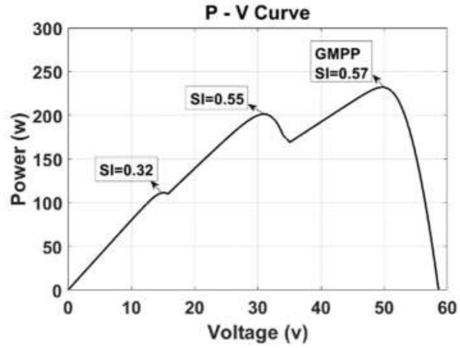

Fig. 4. P-V characteristic of two parallel array in partial shading condition

Thus the modules which receive the same radiation have the same V-I characteristic. Modules with more radiation, which are series with modules that receive less radiation, their working point moves toward open circuit voltage. e.g., considering two modules in two different radiations, the V-I curve of these two modules will be the same as depicted in Fig. 5. If the array voltage is such that no module is bypassed, then the working point of the module with higher radiation moves from point A to point B. In other words, the modulus that is exposed to higher radiation will be in lower current than what it has to be. This means that the voltage of the module, which has more radiation, increases at the GMPP, and the voltage of the modules at the lower radiation, ones which its current is approximately as same as the array current at GMPP, is estimated with VMPPT with a good approximation.

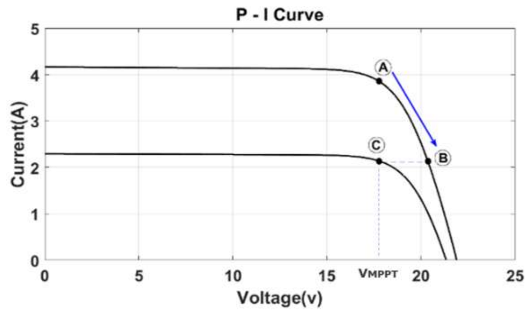

Fig. 5. Voltage and current characteristic of two module in series

In the proposed method, only two open-circuit voltage and maximum power point voltage are used to estimate the array voltage under non-uniform irradiance. The modules that are bypassed their voltage will be the diode drop voltage. According to what is said, assuming an array with Ns series modules (see Fig. 2) which are in partial shading condition, the array voltage is obtained from the following equation:

$$\begin{aligned} V_{string} &= (V_{oc} \times K \times N_n + V_{mppt} \times Nm) \\ &-(Nsh \times V_D) \end{aligned} \tag{10}$$

Nm: number of modules which are in array GMPP.

Nn: number of modules that receive greater radiation than the ones which are in array GMPP.

Nsh: number of modules bypassed by diodes.

V_D: diode drop voltage

K is a factor that its value is calculated from the following equation:

$$K = \frac{V_{oc} + Vmppt}{2Voc} \tag{11}$$

V_{oc} and V_{mpp} are open-circuit and MPP voltage of one module. The V_{mpp} voltage is usually about 0.7 to 0.8 of the open circuit voltage [11]. considering $V_{mpp} = 0.8Voc$, the value of k obtains about 0.9. In the proposed method, the effect of temperature on voltage is considered. Therefore, V_{oc} and V_{mpp} is in actual temperature. So temperature effect takes into account as shown in equation (3).

As an illustrative example in Fig. 6, the number of modules is Ns = 4. The shading patterns are also shown in this figure. it is assumed that one module is being bypassed by the shading index equation due to the fact that this module cannot generate IGmppt current. So, the voltage of this module will be equal to the diode drop voltage. The modules that their current determine maximum current of the array (IGmppt), their voltage will be V_{MPP} and the module with higher irraciance will be at higher voltage (kVoc).

In series-parallel configuration the voltage of terminal is obtained from the following equation:

$$V_t = \frac{1}{N_p} \sum_{k=1}^{k=N_p} (V_{string})_k \tag{12}$$

Where N_p is the number of parallel array, V_{string} is the voltage of k-th array. Total current of the arrays is also calculated from the sum of the arrays current. Therefore, the power of the photovoltaic plant will be obtained by multiplying the estimated terminal voltage from (12) to the total current:

$$P_{tot} = V_t \times (\sum_{k=1}^{N_p} I_k) \tag{13}$$

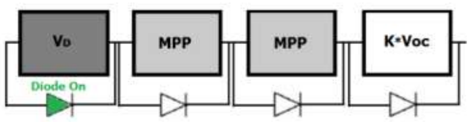

Fig. 6. One array in a shading pattern

V. EXPERIMENTAL AND SIMULATION RESULT

Experimental results are made with the REC220AE module in various climatic conditions. The nominal parameters of this module are: P_{max} = 220 w, V_{mppt} = 28.5 v, I_{mppt} = 7.8 A, V_{oc}=36.5 v, I_{sc} = 8.4 A under standard test conditions (1000 w/m^2, T = 25 c). The coefficient of voltage and current to temperature is -0.34 and 0.06 %/^{o}c, respectively. The converter used in the practical tests is Boost converter which is shown in Fig. 7. The design parameter of the converter are shown in Table I. SMA sensor box is used to measure the irradiance.

In order to evaluate equations (7) to (13), the experimental implementation in two series and series-parallel are provided. Different shading patterns are considered to check the accuracy of the equations as shown in Fig. 9. In these shading patterns, different radiation reaches the solar modules. The module temperature is measured 54.6 degrees. In each pattern, the voltage and current of the array are measured at both local power point and global power points.

A. *Verification of shading index*

To check the validity of the (7), different shading pattern are considered as shown in Fig. 9. The radiation on each module is measured using irradiance sensor. P-V and I-V curves are extracted for each pattern using SIMULINK-MATLAB software. In patterns 1 and 2 there are 3 different radiations so it is expected that three peaks points are P-V curve. Modules with pattern number 2 receive two different radiation on its surface, so it will have two power peaks. For each of the power peaks (Global and local) the SI index is calculated. According to the result SI values show maximum power point correctly. These values are shown in Fig. 8.

B. *Validity verification of estimated maximum power*

After determining where the maximum power point is, the corresponding current is obtained using equation (8). Also the terminal voltage of the array in different partial shading is calculated using (10) and (12). Finally, peak power is calculated. The results of experimental test are shown in Table II. It's clear that errors between estimating values and what is measured from experimental test is less than 3 percent. The proposed equations to find the current and voltage of arrays for local power peaks are also evaluated. For example, in the partial shading pattern number (7), the V-I curve has four peaks point that three of them are local power peaks. the amount of power is estimated and compared with the values obtained in practical test. Their estimated value are P1=344.2, P2=461.93, P3=545.22 and their actual value are P1=360.6, P2=492.1, P3=549.1 . Therefore the power deviation in local power point is less than 6 percent.

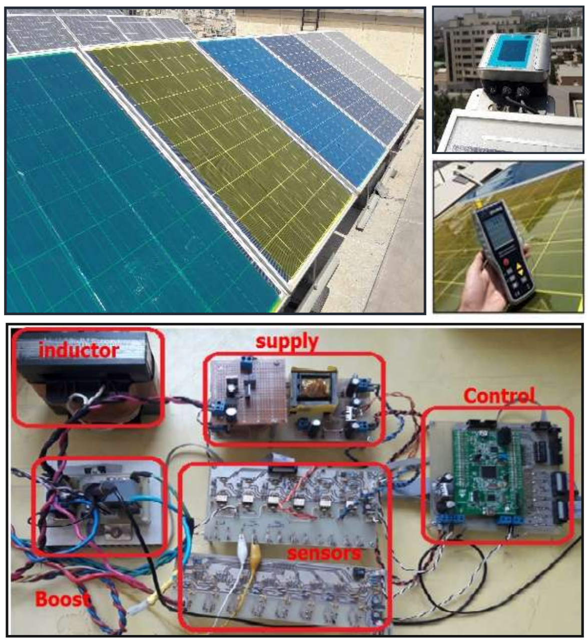

Fig. 7. Boost converter and experimental test board

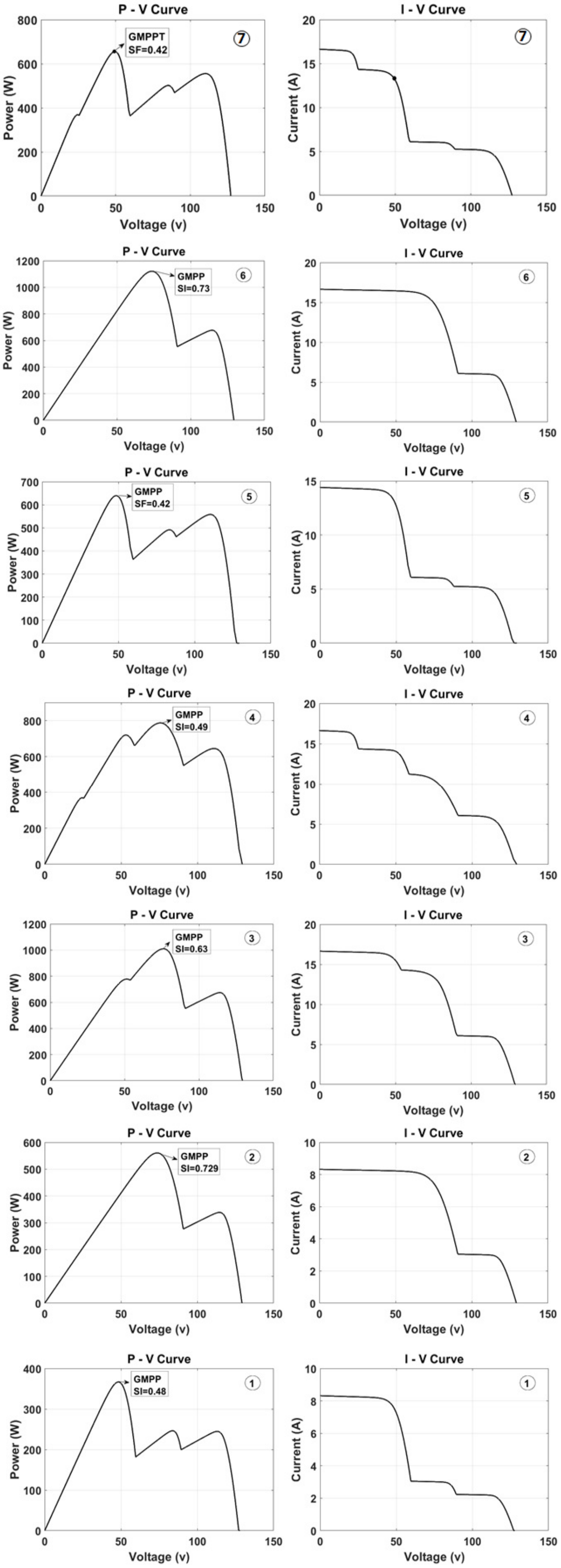

Fig. 8. P-V and V-I characteristic in simulation test

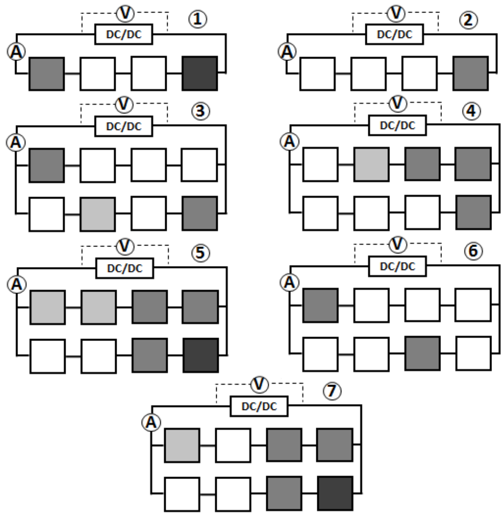

Fig. 9. Shading pattern in experimental test

Table I
converter design parameters

Parameter name	Value
Nominal power	2 kw
Switching frequency	16 khz
Input capacitance	10 uf
Output converter capacitance	470 uf
Inductor impedance	6.5 mh

Table II
Comparing estimation and experimental values

Shading pattern number	Measured power (W)	Power estimation (W)	Power Error (%)	Measured voltage (V)	Voltage estimation (V)	Voltage error (%)
1	359.2	365.51	-1.75	48.47	48.02	0.93
2	552.4	558.93	-1.18	74.26	73.43	1.11
3	1003.6	1030.2	-2.65	76.2	78.22	-2.65
4	788.91	812	-2.92	76	78.22	-2.9
5	639.67	632.5	1.12	48.6	48.02	1.19
6	1021	1096.6	2.17	73.6	73.43	0.23
7	638.4	645.6	-1.12	49.6	49.01	1.18

VI. CONCLUSION

In this paper, a new approach for modeling and estimating the maximum power point of photovoltaic arrays under partial shading condition was proposed. Initially, a parameter which is called shading index was introduced to evaluate the operation of the bypass diode. This index was used to find the global maximum power point location in two series and parallel-series configurations using the meteorological data. It is also possible to estimate the current proportional to the maximum power using this parameter. Then, Voc and Vmppt voltages are used to estimate terminal voltage and consequently, the peak power in both series and parallel-series modules in partial shading condition. These equations also take into account the effect of temperature on voltage. Finally, the proposed modeling and equations were validated through experimental implementation. Different shading patterns were considered to generate different P-V curves and to evaluate the performance of the proposed modeling. It was shown that the estimated power and voltage at maximum power point has less than 3% error compared to actual values. This method also can be used to estimate the amount of local power point with good accuracy.

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