

Photovoltaic Array Modeling under Uniform Irradiation and Partial Shading Condition

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ABSTRACT

Wind energy and solar energy are the prime energy sources which are being utilized for renewal energy. The performance of a photovoltaic (PV) array for solar energy is affected by temperature, irradiation, shading, and array configuration. Often, the PV arrays are shadowed, completely or partially, by the passing clouds, neighboring buildings and towers, trees, and utility and telephone poles. Under partially shaded conditions, the PV characteristics are more complex with multiple peaks, hence, it is very important to understand and predict the MPP under PSC in order to extract the maximum possible power. This paper presents the development of PV array simulator for studying the I-V and P-V characteristics of a PV array under a partial shading condition. It can also be used for developing and evaluating new maximum power point tracking techniques, for PV array with partially shaded conditions. It is observed that, for a given number of PV modules, the array configuration significantly affects the maximum available power under partially shaded conditions. This is another aspect to which the developed tool can be applied. The model has been experimentally validated and the usefulness of this research is highlighted with the help of several illustrations.

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1. INTRODUCTION

Energy production from renewable energy sources such as hydro, wind, tidal, geothermal, bio, and solar are attracting a lot of attentions due to the uprising oil prices, worries about depletion of fossil fuel reservoirs and climate change, and public health concerns [1]. Wind energy and solar energy are the prime energy sources which are being utilized in this regard. Solar energy is abundantly available that has made it possible to harvest it and utilize it properly. Solar energy can be harvested by a standalone generating unit or a grid of connected generating unit depending on the availability of a grid nearby. Photovoltaic system is a critical component to achieve the solar energy through an environmentally-friendly and efficient way [2]. The performance of PV module is affected by the solar irradiance and cell temperature [3]. However, the level of solar irradiance mainly affect the electricity generation from the PV module. When PV module receives uniform solar irradiance, the array will present non-linear I - V and P - V characteristic.

The PV module has an optimal operating voltage point which is called Maximum Power Point (MPP). At this particular optimal voltage, the PV module provides maximum power. The use of the power control mechanisms called the Maximum Power Point Tracking (MPPT). The most popular configuration PV power system is the series-parallel combination [4]-[5]. Series connections are responsible for increasing the voltage of the module whereas the parallel connection is responsible for increasing the current in the array. At the same solar irradiance level and cell temperature, the PV array will generate same amount of current as

the single module. It is quite simple to determine the MPP when PV array is uniformly exposed to solar irradiance, but when the PV array is operated under partial shading condition (PSC), one or more of the PV modules in the array received less amount of solar irradiance. Under PSC, the shaded module will cause the generating current of the entire PV array being limited and the characteristics become more complicated with the occurrence of multiple peaks [6]. The conventional MPPT is not able to distinguish between local and global MPP and is easily trapped into local MPP such that the power generated by the PV array will be limited [7]-[8].

The optimization algorithm selected for MPPT should ideally have the properties of simple computational steps, faster convergence, and guaranteed convergence to global MPP (GMPP) together with the feasibility of implementation in a low-cost digital controller. In this paper, we have developed PV array simulator for analyzing, simulating, and evaluating the effects of PSC on PV arrays.

2. RESEARCH METHOD

The simulator design according the I–V and P–V characteristics of a partially shaded PV array. It is important to understand how the PV array structure and the shading pattern are defined in the proposed study. This procedure consists of designing of a single PV module and PV array in partial shading condition, which is described in details as the following sections.

2.1. Single PV module

PV module is built up with combined series combinations of PV solar cells, which are usually represented by a simplified equivalent circuit model such as the one given in Figure 1. This model contains a current source I_{PV} , a diode D , and a series resistance R_s , which represents the resistance inside each cell and in the connection between the cells [9].

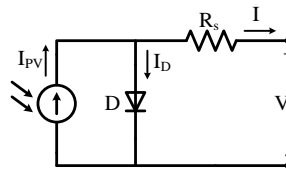


Figure 1. Simplified-equivalent circuit of photovoltaic cell

The net current I is the difference between the photocurrent I_{PV} and the diode current I_D [10]-[11] is given as

$$I = I_{PV} - I_o \left[\exp \frac{q}{Ak_B T} (V + IR_s) - 1 \right] \quad (1)$$

A number of PV cells are connected in series to generate useful DC voltage. The output current PV module is described by

$$I = I_{PV} - I_o \left[\exp \frac{q}{N_s Ak_B T} (V + IR_s) - 1 \right] \quad (2)$$

PV cell converts sunlight directly into electricity which the electrical operating point of the module is able to be adjusted to deliver maximum available power.

2.2. PV array in partial shading condition

PV array consists of multiple modules, connected in parallel and series. For simulating an entire PV array, each PV module comprises N_s PV cells connected in series, which current equation can be described as in (3).

$$I = \left[I_{PV} - I_o \left[\exp \frac{q}{nN_s A k_B T} (V + I R_s N_s) - 1 \right] \right] \quad (3)$$

In this proposed design, the PV array is divided into substring modules involved for each bypass diode as shown in Figure 2. By using (3), the output current of each module can be obtained, where n is the number of PV modules in one string. The output current of PV module must be arranged from highest to lowest values.

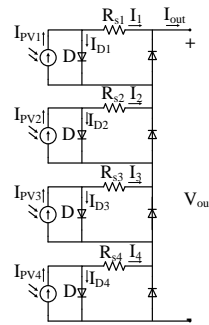


Figure 2. Circuit model of string consist of four series connected module

The most shaded module determines the output current on the last step of the staircase I-V curve with the largest corresponding voltage as shown Figure 3. In accordance with the assumption of a single bypass diode for each PV module, if the partial shading occurs in the PV module, the lowest irradiance level will be considered. The analysis based on the observation of the output current of PV module, selecting the maximal value is required to obtain the string current as shown in Figure 4.

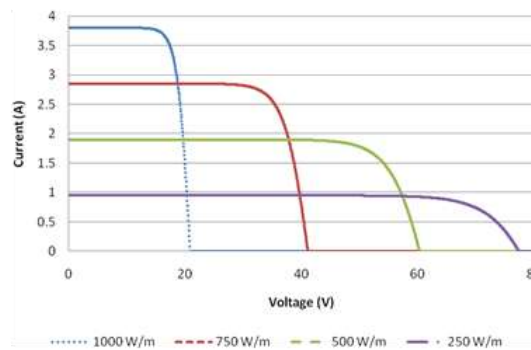


Figure 3. Output current each module according to various irradiance

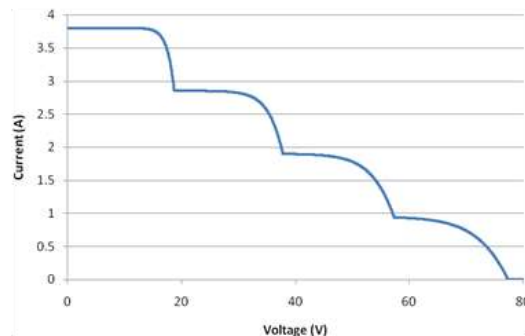


Figure 4. Partial shaded condition in four stairs I-V curve with bypass diode

The output current of PV array is the summation of the output current each string according to Equation (4).

$$I_{PV} = I_{S1} + I_{S2} + I_{S3} + \dots + I_{Sk} \quad (4)$$

Where I_{Sk} is output current of string, k is the number of string, with the bypass diode for each PV module, the maximum current among all string in each voltage will be selected.

2.3. PV array simulation flowchart

The output of the PV array varies mostly with two environment conditions which are solar irradiation and temperature. The I-V and P-V characteristics become complicated under partial shading that occurs due to the passing clouds, flying birds, nearby building shadow, trees, etc.

Figure 5 shows the complete flowchart of the proposed PV array simulator. In the step (1), the initial variables are defined as follows: A is ideality factor of diode, k_B is the Boltzmann constant, q is the electron charge, n is the series PV modules, and k is the number of string. The arbitrarily temperature and shading pattern is set in the step (2). By using Equation (3-3), the output current of PV module according to the photocurrent and the reverse saturation current can be calculated in step (4). In the step (5), the output power of PV module is calculated by multiplying the output current and voltage. This cycle is done as much as the number of used PV module. The maximal value of the current and power are chosen in the step (7). If all of the string has been checked, the output current and output power of PV array are calculated by using step (9). These I-V and P-V characteristic curves of the PV array will be obtained.

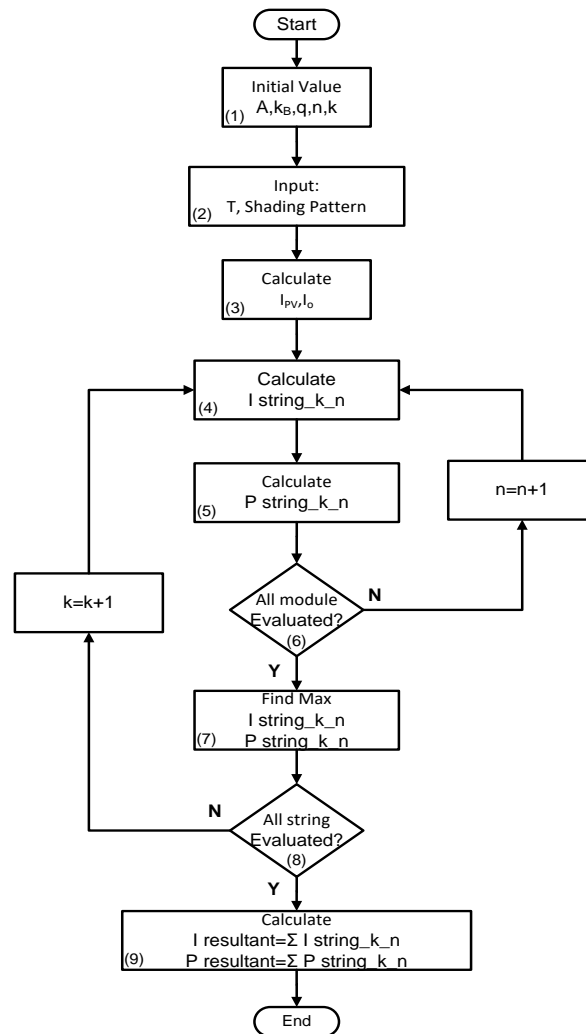


Figure 5. Flowchart PV array simulator under partial shading condition

3. RESULTS AND ANALYSIS

The availability of the simulator in the Matlab platform is seen as an advantage from the perspective of researchers and practitioners alike as this software has almost become a standard in various engineering discipline. The model will be evaluated using Matlab/Simulink [12] and the proposed simulator in C++ language.

3.1. PV module simulation

In order to validate the modeling and simulation PV module, the model output is compared with PV developed model that has been conducted in Matlab/Simulink. The simulation is under Standard Test Conditions (STC): irradiance intensity of $1000W/m^2$, $1.5AM$ standard reference spectrum [13], and cell or module temperature of $25^{\circ}C$. The I-V characteristic curve generated using Simulink and C simulator curves can be seen in Figure 6.

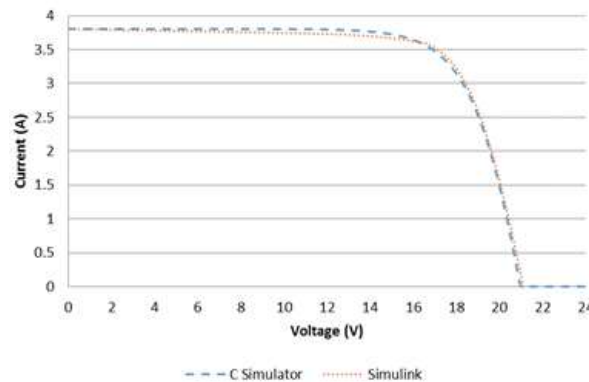


Figure 6. The I-V characteristics curves generated by Simulink (in red) and C Simulator (in blue) and superimposed together

The PV current values generated by these two simulators are compared to obtain the error value as shown in Table 1. Figure 7 shows the P-V curves generated by Simulink (in red) and C Simulator (in blue) and are superimposed together to compare the occurred shifting. According to the Figure 7, error values of these two simulators can be obtained as shown in Table 2.

Table 1. Comparison I-V Results of PV Current Generated under Standard Test Conditions.

Simulator	Voc (V)	Isc (A)	Vmpp (V)	Impp(A)
Simulink	21.1	3.8	17.19363	3.51335
C Simulator	21	3.799	16.8	3.48
Error (%)	0.47619	0.002	2.289419	0.958333

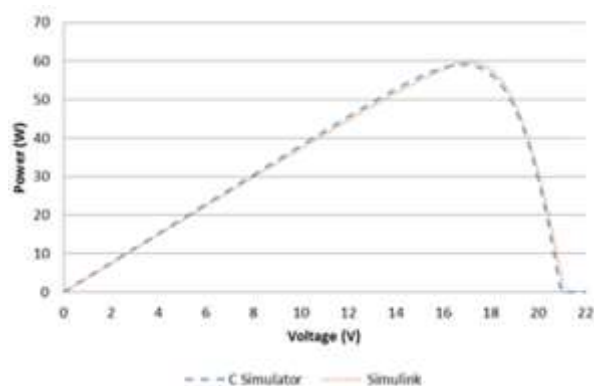


Figure 7. The P-V characteristics curves generated by simulink and C simulator

Table 2. Comparison P-V Results of PV Power Generated under Standard Test Conditions

Simulator	V _{mpp} (V)	I _{mpp} (A)	P _{max} (W)
Simulink	17.19363	3.51335	59.83385
C Simulator	16.8	3.48	59.0244
Error (%)	2.289419	0.958333	1.352826

3.2. PV array simulation

In reality, PV arrays do not receive uniform insulations at all the time because some part of the PV arrays might be shaded. Under shaded conditions, the shaded modules behave as a load instead of generator, which produce the hot spot problem [8], [10]. This problem can be avoided by driving the current of non-shaded PV modules through the bypass diode. The proposed simulator must be capable to replicate the effects of this diode. For illustration, an example of single string simulation with partial shading condition is shown in Figure 8.



Figure 8. Operation of single string PV array: The un-shaded module has solar insolation $L=1000 \text{ W/m}^2$, shaded module has $L=500 \text{ W/m}^2$

The I–V and P–V curves from C Simulator are shown in Figure 9 and Figure 10. Each simulator will be simulated in three different cases, for all these shading cases as given in Table 3. It can be seen that bypass diodes of a PV module can reduce absorbing power of shaded module within the PV string and improve the performance of PV system.

Table 3. Tested shading cases

Case	Shaded Modules	Bypass Diode
1	Module 1=1000 W/m^2	Yes
	Module 2=1000 W/m^2	
	Module 3=1000 W/m^2	
	Module 4=1000 W/m^2	
2	Module 1=500 W/m^2	Yes
	Module 2=1000 W/m^2	
	Module 3=1000 W/m^2	
	Module 4=1000 W/m^2	
3	Module 1=500 W/m^2	No
	Module 2=1000 W/m^2	
	Module 3=1000 W/m^2	
	Module 4=1000 W/m^2	

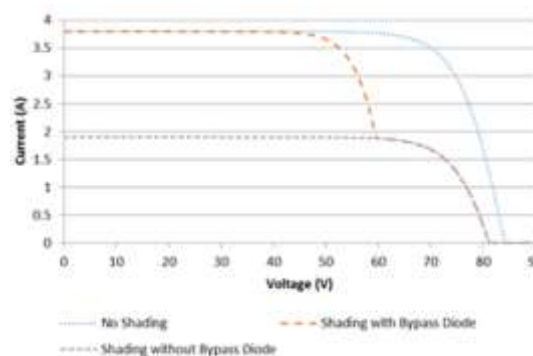


Figure 9. The I-V characteristics curve generated by C Simulator which three cases

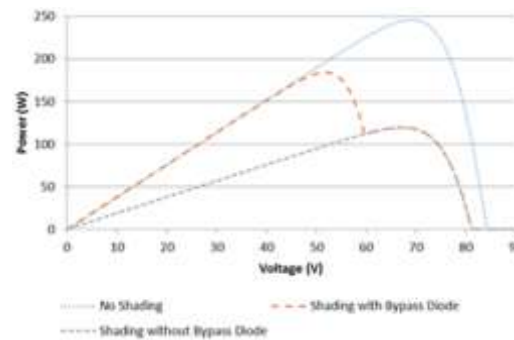


Figure 10. The P-V characteristics curve generated by C Simulator which three cases

4. CONCLUSION

The aim of this study is to develop simulator to obtain the I-V and P-V characteristics of a PV array. A model of the one diode PV cell was used, modified and then implemented in a PV array setup using the C++. In this simulator, several simulations were conducted under different configurations, varying irradiation levels and temperatures. Satisfactory results from these simulations were achieved and the process validates the performance of a PV array under STC, partial shading and varying conditions due to the comparison with the reference [12]. In addition, due to the overall performance of the PV panels/array, the effect of series and/or parallel combinations was also validated. The I-V and P-V characteristics clearly show that multiple peaks were obtained under partial shading conditions. These multiple peaks increased due to the increasing of the shading patterns. The results obtained with this simulator can be effectively used to investigate the effectiveness of the MPPT methods working under partial shading conditions. Digitally controlled MPPT can be directly used in the simulated system and can be evaluated without having to build and modify an expensive prototype.

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Lunde Ardhenta received the M.S. degree in Department of Electrical Engineering, National ChiaYi University, Taiwan in 2015. He completed his Bachelor degree in Department of Electrical Engineering, University of Brawijaya, Indonesia in 2011. His research interests include renewable energy applications, nonlinear control and digitalized control techniques for power electronics apparatus and systems, and optimal control theory.



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