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A CAD Package for Modeling and Simulation of PV Arrays under Partial Shading Conditions

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Abstract

A computer-aided design CAD package, with a graphical user interface (GUI), to aid the design and analysis of two-dimensional photovoltaic (PV) arrays under partial shading conditions is presented. The package uses a variant of the two-diode model of a PV cell and has been developed using MATLAB. The simulation model allows insolation to be set for each PV module individually, which is a major advantage of the package. The effects of partial shading and temperature on the electrical characteristics of PV arrays were successfully investigated using the package. Results obtained from the simulation were in good agreement with the manufacturers' datasheets.

Keywords: MATLAB; modelling; simulation; photovoltaic; partial shading.

1. Introduction

Oil and gas fuels have been man's main sources of energy for more than a century. Unfortunately, these sources have some acute problems: they are harmful to the environment, non-sustainable, insecure and their prices are soaring. Problems such as these led to increased interest in renewable energy sources such as wave, wind, and solar which are clean and sustainable.

Due to their relative costs and reduced maintenance overheads, photovoltaic (PV) systems have been gaining popularity. At the heart of any PV system is the photocell, which converts the light energy from the sun into electrical energy. For practical reason, a large number of such cells are normally connected together to form a PV panel or module. Panels are then connected in series-parallel combinations to obtain the required terminal voltage and output power. The terminal I-V characteristic of a PV module resembles that of a constant current source as shown in Fig. 1, which also includes a plot of the cell's P-V (power-voltage) output curve.

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Nomenclature

q	Electronic charge $= 1.6021765 \times 10^{-19}$ (C).
k	Boltzmann's constant $1.3806503x10^{-23}$ (JK^{-1}).
ΔT	Change in temperature (^{o}C).
G	Insolation level (W/m^2).
G_o	Standard insolation levelof 1000 (W/m^2).
STC	Standard test conditions at 25 ^{o}C.
K_I	Short-circuit current coefficient (A/C^o).
K_V	Open-circuit voltage coefficient (V/C^o).
R_P	Shunt resistance of a PV cell (Ω).
R_S	Series resistance of a PV cell (Ω).
a_n	Ideality factor of the nth diode.
I_{Sn}	Saturation current of diode n (A).
I_{mp}	Current at maximum power point.
I_{PV}	Photovoltaic generated current (A).
I_{SC}	Short-circuit current (A).
V_{mp}	Voltage at the maximum power point.
V_{OC}	Open-circuit voltage (V).
V_{Tn}	Thermal coefficient of the nthdiode kTq^{-1} (V).
P_{mp}	Maximum power developed (W).

Probably, the most important parameter of a PV panel is the maximum power point (MPP) on which the panel must be operated for maximum efficiency. However, since the I-V characteristic varies with the insolation and with temperature, the MPP also varies and a maximum power point tracker MPPT is therefore, a crucial component of any PV system. The problems are compounded by the effects of partial shading. When a PV system consists of a large number of PV panels, it is very difficult to ensure that all panels are subjected to the same level of insolation. Different panels due to factors such as dust, clouds, trees, etc. will in practice be subjected to different amounts of insolation [1]. This is known as partial shading and can give rise to complex I-V and P-V characteristics such as multiplicity of power peaks as shown in Fig. 2, which shows the presence of local maximum power points in addition to the global maximum point. This puts onerous demands on the MPPT requirements, as it has to distinguish between local and global maximum power points.

Investigation of the effects of partial shading is therefore, an integral part in the design process of any

PV system. In order to analyze the behaviour of a PV array under varying conditions of insolation and temperature, an accurate circuit model of a PV cell is required.

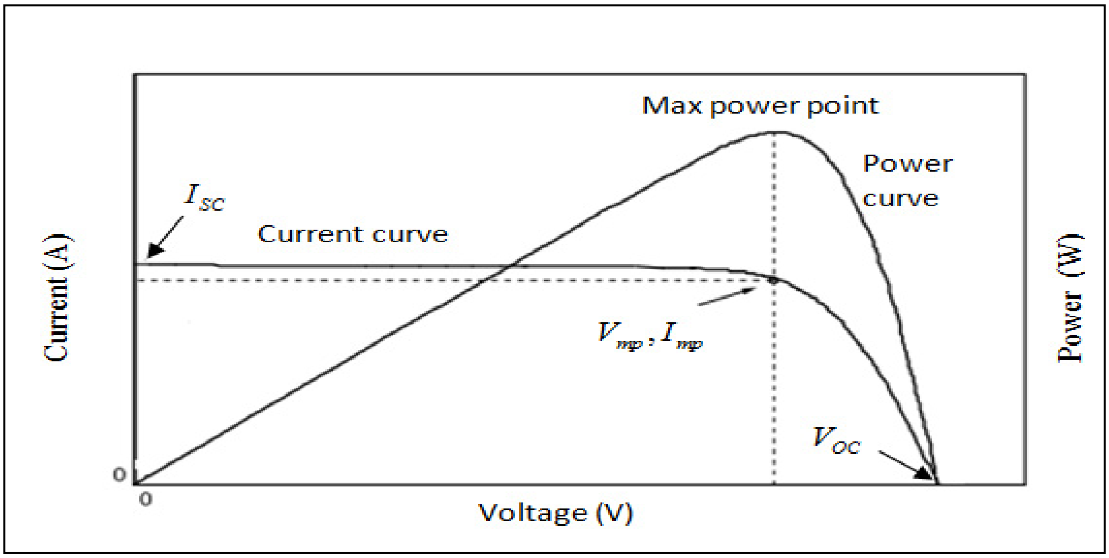

Fig. 1.The I-V and P-V characteristics of a typical PV panel.

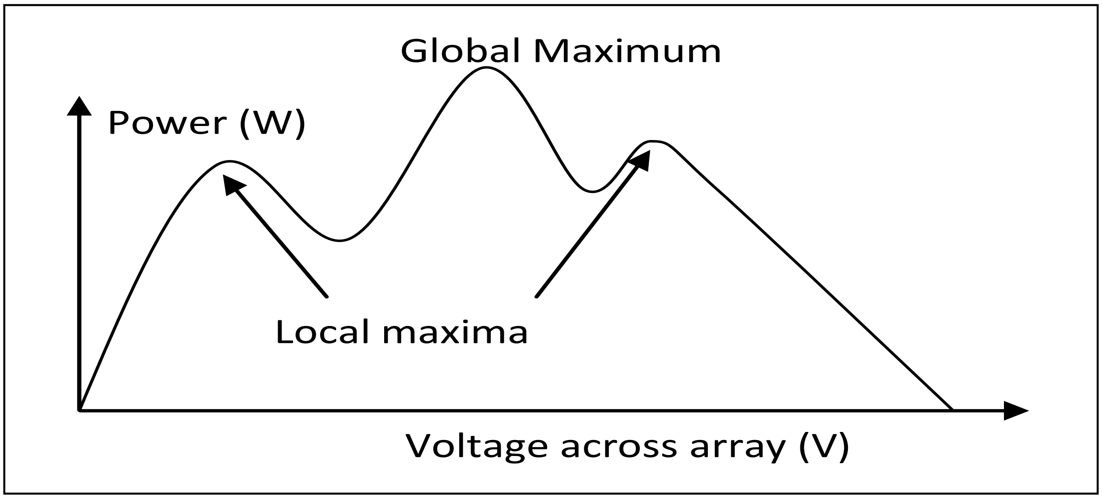

Fig. 2.The effect of partial shading on the P-V characteristics of typical PV array.

Many researchers, in pursuit of simplification, used different approaches for modeling PV cells. The most basic PV model consists of a single diode with a photocurrent source [2-3]. This model was later improved by the inclusion of a series resistance to account for the internal contact voltage drop [4-8]. A parallel resistance was also added to the model as shown in Fig. 3 to cater for effects such as the finite output resistance of a cell [9-11]. However, in this single-diode model, the effects of the carrier recombination loss whose effects are more profound at lower levels of insolation have been ignored [12]. Further research led to variants of the above model which included a second diode to account for the effect of recombination of charge carriers [12-13]. A three-diode model has also been proposed in the literature which attempts to produce a piecewise linear model [14]. In this paper, a model similar to that in [13] has been developed with improvements in the reverse saturation current, flexibility in diode parameters and reduced computation time. The model was used to develop a MATLAB CAD package with a graphical user interface (GUI). The package allows the designer to investigate the effects of partial shading and temperature upon the electrical characteristics of a given configuration of PV panels. Many researchers studied the effects of partial shading on the PV characteristics, e.g. [15-20]. However, their work is either focused at PV cell/module level or they have used an impractical model which does not consider effects normally dominant in partial shading such as low levels of insolation. Reference [15] presents a two-diode model simulation based on numerical technique but without using any bypass and blocking diodes. This can lead to significant loss of output power from the system [17]. Other researchers in studying the effects of partial shading used unrealistic shading conditions [18] such as assuming uniform shading on a large section of a PV array. This paper proposes a technique for simulating a large PV panel using MATLAB. The proposed technique was used to study the effects of varying shading and temperature conditions on the electrical characteristics of PV arrays. The PV array model uses an improved two-diode model and realistic partial shading conditions by allowing the insolation to change at individual module level.

2. The Proposed Model

2.1. PV Cell Model

A single-diode model is shown in Fig. 3 whose output current equation is

$$I = I_{PV} - I_S \left[\exp\left(\frac{V + IR_S}{aV_T} \right) - 1 \right] - \left(\frac{V + IR_S}{R_P} \right) \tag{1}$$

where I_{PV} is the generated photovoltaic current, I_S and a are the reverse-saturation current and the ideality factor of the diode respectively, whilst V_T is the thermal equivalent voltage defined in terms of the Boltzmann's constant k, the temperature T (K) and the electronic charge as $V_T = kT/q$ and is approximately equal to 25 mV at room temperature.

The resistors R_S and R_P are the series and parallel resistances, respectively. Earlier work on partial shading using only one diode and the single series resistance model were ineffective in large PV arrays at low insolation levels i.e. when the effects of recombination becomes important. For this reason, the two-diode model, Fig. 4, becomes more appropriate. In this model, the second diode accounts for the low-insolation, whilst the parallel resistor accounts for the effects on the open-circuit voltage at higher temperatures. The equation of the output current for the two-diode is

$$I = I_{PV} - I_{S1}\left[\exp\left(\frac{V + IR_S}{a_1 V_{T1}}\right) - 1\right] - I_{S2}\left[\exp\left(\frac{V + IR_S}{a_2 V_{T2}}\right) - 1\right] - \left(\frac{V + IR_S}{R_P}\right) \quad (2)$$

Where I_{S1}, I_{S2} are the saturation currents, a_1, a_2 are the ideality factors; V_{T1}, V_{T2} are the thermal voltages of diodes D_1, and D_2, respectively.

The photovoltaic current I_{PV} at a given temperature and irradiance is

$$I_{PV} = \left(I_{PV(STC)} + K_I \Delta T\right) \times \left(\frac{G}{G_o}\right) \quad (3)$$

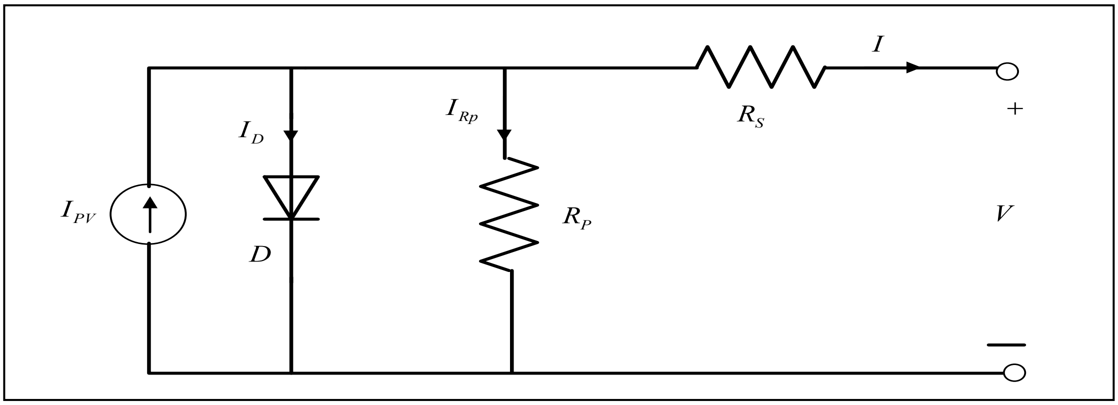

Fig. 3. A single diode PV cell model

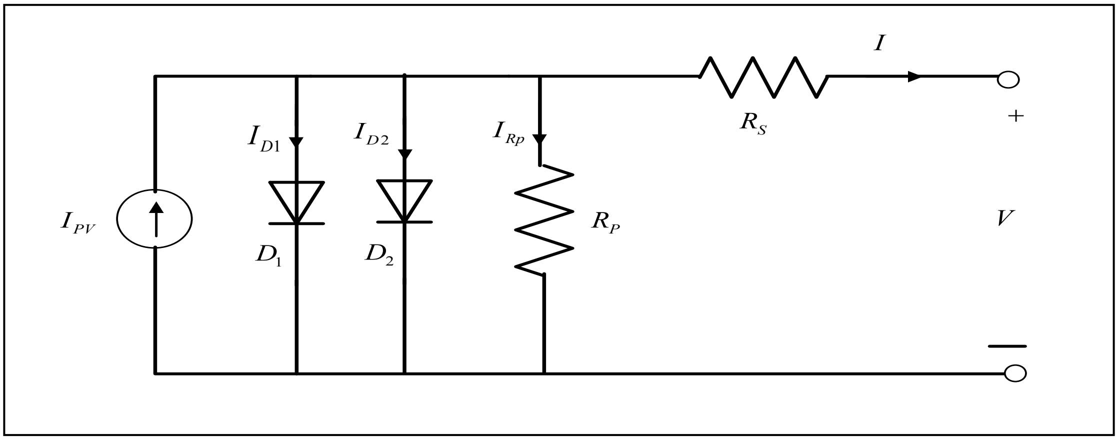

Fig. 4.A two-diode PV cell model.

where $I_{PV(STC)}$ is the photovoltaic current at the standard test conditions i.e. when $G = G_o$, K_I is short-circuit current coefficient, ΔT is the change in temperature in Kelvin, G is the surface irradiance of cell and $G_o = 1000\ (W/m^2)$ is standard irradiance.

$I_{PV(STC)}$, proposed in [9] is

$$I_{PV(STC)} = \left(\frac{R_P + R_S}{R_P}\right) I_{SC(STC)} \tag{4}$$

The open-circuit voltage as a function of temperature

$$V_{OC} = \left(V_{OC(STC)} + K_V \Delta T\right) \tag{5}$$

Where $V_{OC(STC)}$ is the open-circuit voltage at STC and K_V is the open-circuit voltage coefficient. The improved reverse saturation current equation at given temperature, proposed by [21] is

$$I_S = (I_{PV} - \frac{V_{OC}}{R_P}) \Big/ \left[\exp\left(\frac{V_{OC}}{aV_T}\right) - 1\right] \tag{6}$$

For the two-diode model, I_{S2} is taken to be 1 to10 times I_{S1} and for simplification they are kept equal in the following equation

$$I_{S1} = I_{S2} = \left[I_{PV} - \left(V_{OC} / R_P\right)\right] \Big/ \left[\exp\left(\frac{V_{OC}}{a_2 V_{T1}}\right) + \exp\left(\frac{V_{OC}}{a_1 V_{T2}}\right) - 2\right] \tag{7}$$

The resistors R_S and R_P are obtained using analytical technique described in [13] which matches the maximum power point $P_{mp} = V_{mp} I_{mp}$ unique to the R_S and R_P combination. The values of a_1 and a_2 can be arbitrarily chosen to fit the curve and in this paper $a_1 = 1.2$, and a_2 can be chosen with a suitable value to fit the curve. In the above equations, $V_{OC(STC)}$, $I_{SC(STC)}$, V_{mp} ,, I_{mp}, K_V and K_I are usually found in manufacturers' datasheets.

3. Simulation Results

The MATLAB based CAD package with a graphical user interface (GUI) described in this paper allows the user to simulate a two-dimensional array of PV modules with different levels of shading as suggested by Fig. 5. A snapshot of the front-end of the package is shown in Fig. 6. The package allows the user to specify the type of the PV model e.g. Bp MSX 60 [22], the number of parallel paths and the number of modules in series in each path.

The user also specifies the insolation per module, which is more realistic than earlier approaches of assuming a complete parallel path is under the same level of shading. Finally, the temperature of each module can be specified.

The package was used to simulate the operation of 450 PV MSX 60 modules arranged in 45 parallel paths with 10 units in series per path. The resulting P-V characteristic of the PV array is shown in Fig. 7.

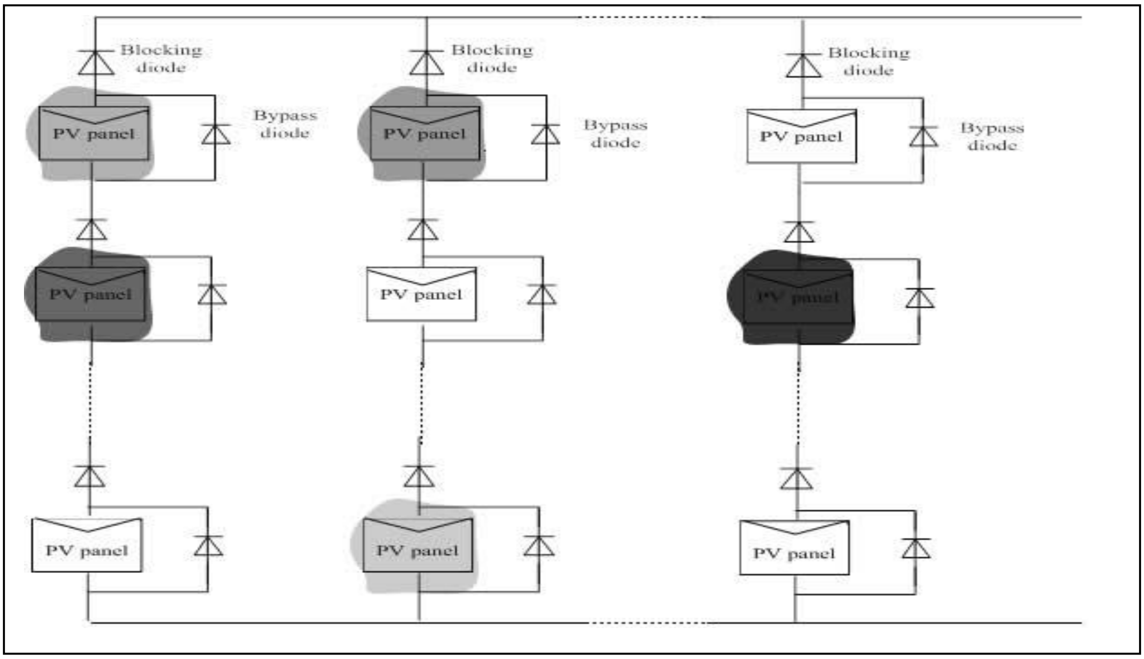

Fig. 5. The insolation can be specified for each individual module as depicted by the intensity of the gray shading.

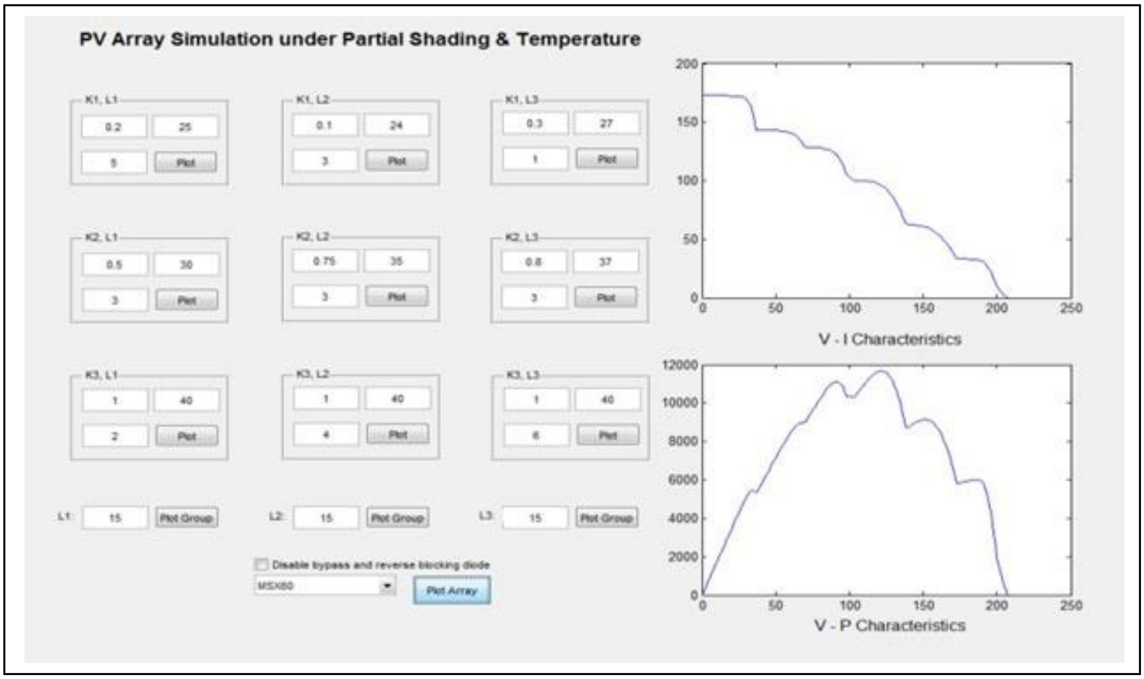

Fig. 6. A snapshot of the CAD package, which also includes the I-V and P-V characteristics of a PV array.

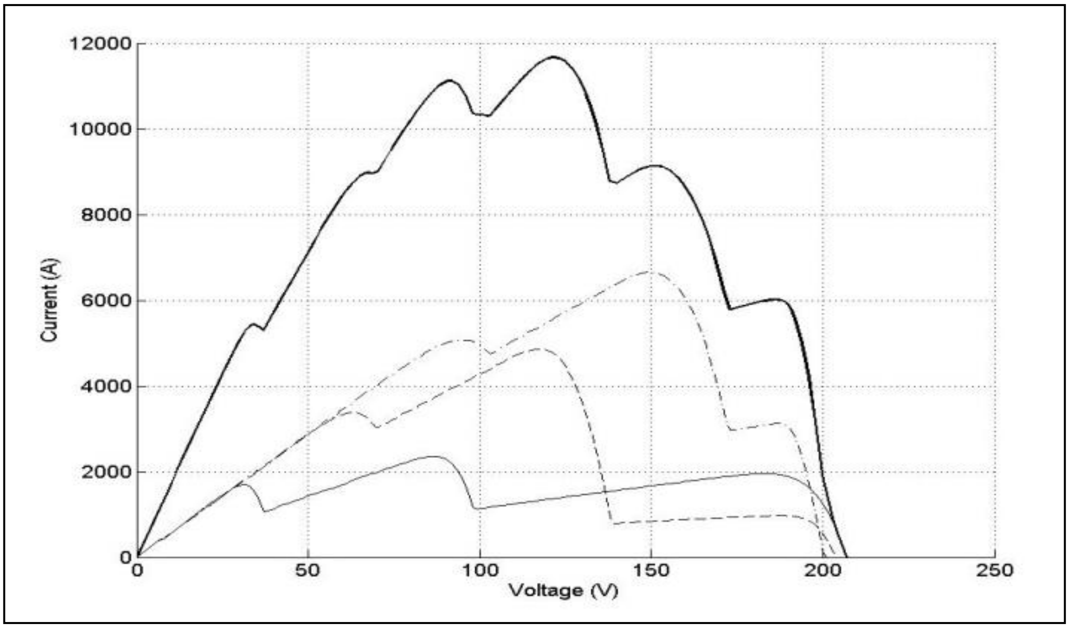

Fig. 7.P-V characteristics of PV Array showing multiple peaks due to partial shading.

4. Conclusions

A CAD package with a graphical user interface to aid the design and analysis of PV arrays has been developed and used to investigate the effects of partial shading using a number of commercially available PV modules. Results obtained from the simulation were in good agreement with the data obtained from the manufacturers' datasheets.

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