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Single-Diode Model and Two-Diode Model of PV Modules: A Comparison

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Abstract— **This paper proposes a comparison between single-diode model and two-diode model of photovoltaic (PV) module. The main concern of this work is the accuracy, number of unknown parameters, and the execution time for the unknown parameters, under standard test conditions (STC), in each model. The proposed work tests the accuracy of both models under different temperature conditions using two types of solar modules. The accuracy of each model is tested in terms of maximum power and maximum voltage, and compared to justify the pros and cons of each model.**

***Keywords*—photovoltaic; two-diode model; single-diode model; parameters extractions**

I. INTRODUCTION

The solar power is clean and almost maintenance free source of energy, which is able to generate electricity while greenhouse emissions are reduced. The PV system converts sunlight to electricity using the basic device of this system, which is the PV cell. On the other hand, because of the high investment cost on PV modules, optimal use of the available solar energy has to be ensured. This necessitates a precise and reliable simulation of the designed PV systems prior to installation. The most important component that affects the accuracy of simulation is the PV cell modeling [1-4].

Usually PV cells are connected in series and/or parallel to form what is called PV modules. These modules can be connected again in series and/or parallel to form the PV panels, which can be grouped to form PV arrays. The term array is used most of the time to present PV panels [5]. Most of the time, research is done primary on PV panel/module modeling.

In contrast, it is essential to operate the PV systems near/at the maximum power point to enhance the efficiency of the PV system. However, there is a nonlinear nature of PV system appears clearly in Fig. 1 [6], i.e. the current and power of the PV array depends on the array terminal operating voltage. On the other hand, the maximum power operating point varies with temperature and irradiation level. Short-circuit current decreases with the decrease in irradiation which is obvious since they possess linear relationship. At the same time the power at maximum power-point decreases with the increase in temperature.

II. PHOTOVOLTAIC SYSTEM

A photovoltaic (PV) system converts sunlight into electricity directly. These systems can be sited in or near where the requirement takes place, hence avoiding losses of transmission and contributing to the reduction of CO_2 emission in urban center [7].

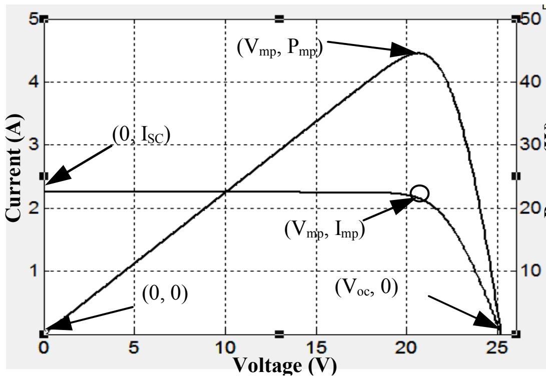

Figure 1. Output characteristics of PV cells

The basic device of a PV system is the photovoltaic (PV) cell, while the conversion unit in this generation system is the photovoltaic module [8] as shown in Fig. 2. The harvested energy depends on solar radiation, the temperature of the cell and the voltage produced in the photovoltaic module. In general, the larger area solar panels will produce more energy than the smaller solar panels, under the same conditions.

The voltage and current available at the terminals of a PV device may directly feed small loads. More complicated applications require electronic converters to produce the electricity from the PV device [8].

A. Photovoltaic cell model

The photovoltaic cell is the basic unit of a photovoltaic module and it is the element in charge of transforming the sun rays or photons directly into electric power.

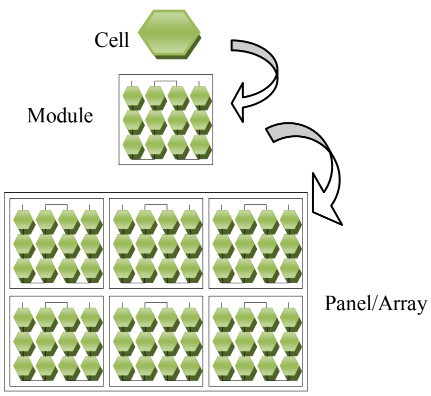

Figure 2. Cell, module and array models

Photovoltaic cells consist of a p-n junction fabricated in thin wafer or layer of semiconductors, whose electrical characteristics differ very little from a diode represented by the equation of Shockley [9]. Most of the commercial PV panels in the market are made of silicon (Si), although Si is not the only, and probably not the best, semiconductor material for PV cells, but it is the only one whose fabrication process is economically feasible in large scale. Other materials can achieve better conversion efficiency, but at higher and commercially unfeasible costs [6].

PV module modeling primarily involves the estimation of the non-linear I–V curves [10-12]. Previous researchers have utilized circuit topologies to model the characteristics of the module when subjected to environmental variations such as changed in irradiance and temperature. There are currently two main lumped circuit models in use. The first one is the *Single-Diode Model* as shown in Fig. 3, described by the modified Shockley diode equation [13]. The second model commonly referred to as the *Two Diode Model* (*Double-Diode Model*) shown in Fig. 4, which is more accurate representation of solar cell behavior than the single-diode model. The single- diode model is particularly inaccurate in describing cell behavior at low illuminations. However, these circuit models are based on assumptions. The main assumption is that of linearity, namely that the current flowing through the cell is a superposition of two currents, one due to junction bias and the other due to illumination as shown in Fig. 5 [14]. These assumptions may not be accurate, but these models do generally fit experimental I-V characteristics fairly accurately, and can provide a very useful tool in assessing cell performance provided the model parameters are easily obtainable. The model parameters can also be a useful tool for monitoring solar-cell manufacturing processes if the parameter values can be determined simply and rapidly.

B. Single diode model

By far, the simplest approach is the single diode model i.e. a current source in parallel to a diode as shown in Fig. 4 where the output of the current source is directly proportional to the light falling on the cell. This model only requires three parameters to completely characterize the I–V curve, namely short-circuit current (I_{sc}), open circuit voltage (V_{oc}) and diode ideality factor "a" [12]. In fact, single diode model does not adequately represent the behavior of the cell when subjected to environmental variation, especially at low voltage [10-12]. An improvement of this model is done by the inclusion of one series resistance, R_s [15]. This model is known widely as the R_s-model. Due to its simplicity and computational efficiency, the R_s model is by far the most widely used model in PV system simulation. However it exhibits serious limitations when subjected to temperature variations; its accuracy is known to decline at high temperature. Further extension of the R_s-model, called as the R_p-model, which includes an additional shunt resistance R_p was introduced [16]. This model which is shown in Fig. 3 is more practical (R_p-model), where R_s and R_p represent the series and parallel resistances, respectively. The output current equation for the R_p-model can be written as in Eq. (1)

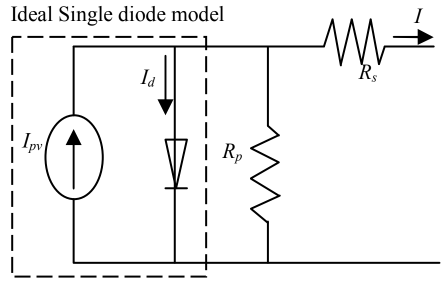

Figure 3. Single diode model

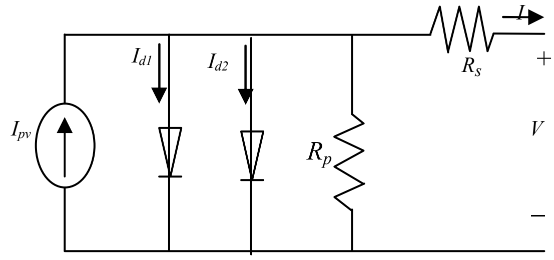

Figure 4. Two diode model

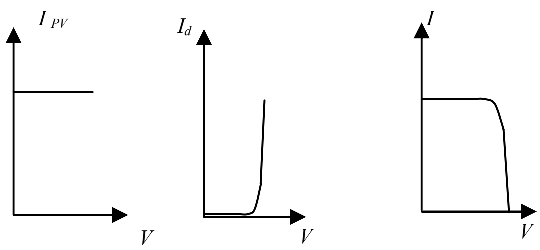

Figure 5. I-V characteristic curve

$$I = I_{pv} - I_o\left[\exp\left(\frac{V + IR_S}{aV_T}\right) - 1\right] - \left(\frac{V + IR_S}{R_P}\right) \quad (1)$$

Where:

I_{PV} is the current generated by the incidence of light,
I_o is the reverse saturation current,
V_T (=kT/q) is the thermal voltage of the PV module,
q is the electron charge (1.60217646×10^{-19} C), k is the Boltzmann constant (1.3806503×10^{-23}J/K),
"a" is the diode ideality factor ,
R_s and R_p are the equivalent series and parallel resistances, respectively.

Fig. 5 [6] shows the characteristic I-V curve of the ideal/simplest PV cell shown in Fig. 3 that composed of the light generated current I_{PV} and the diode current I_d, where the light-generated current of the module depends linearly on solar irradiation and is also influenced by temperature as shown in Eq. 1 [9, 10].

The well known diode saturation current equation is given by Eq. (2) [14]:

$$I_o = I_{o,STC}\left(\frac{T_{STC}}{T}\right)^3 \exp\left[\frac{qE_g}{ak}\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right] \quad (2)$$

where: E_g is the band gab energy of the semiconductor, $I_{o,STC}$ is the nominal saturation current at STC.

An improved equation to describe the saturation current which considers the temperature variation is given in Eq. (3) [6]:

$$I_o = \frac{\left(I_{sc,STC} + K_I \Delta T\right)}{\exp\left[\left(V_{oc,STC} + K_V \Delta T\right)/ aV_T\right] - 1} \quad (3)$$

Where:

K_I is the short circuit current coefficient,

($\Delta T = T - T_{STC}$) (in Kelvin, T_{STC} =25 □C),

G is the surface irradiance of the cell (W/m²) and

G_{STC} (1000 W/m^2) is the irradiance at STC.

K_V is the open circuit voltage coefficient.

At the open circuit voltage V_{oc}, the R_p-model shows a different approach from the experimental data, suggesting that the R_p-model is insufficient when dealing with low irradiance levels [17]. This gives a prediction to have significant implications during periods of partial shading. On the other hand, the single diode model was based on the assumption that the recombination loss in the depletion region is absent; where in a real solar cell the recombination represents a substantial loss, especially at low voltages. This cannot be adequately modeled using a single diode [10].

C. *Two diode model*

On the other hand, there is another model that represents the PV cell more accurately while it needs additional number of unknown variables, known as the two-diode model. The proposed two-diode model and the R_p-model exhibit similar results under STC. However, as irradiance gets lower, more accurate results are obtained from the two-diode model, especially in the vicinity of the open circuit voltage V_{oc}. Although greater accuracy can be achieved using this model, it requires the computation of seven parameters, namely I_{PV}, I_{o1}, I_{o2}, R_p, R_s, a_1 and a_2 instead of five unknown parameters in the R_p-model. The output current equation of the two diode model shown in Fig. 4 can be written as in Eq. (4).

$$I = I_{pv} - I_{o1}\left[\exp\left(\frac{V + IR_S}{a_1 V_{T1}}\right) - 1\right] - I_{o2}\left[\exp\left(\frac{V + IR_S}{a_2 V_{T2}}\right) - 1\right] - \left(\frac{V + IR_S}{R_P}\right) \quad (4)$$

where I_{o1} and I_{o2} are the reverse saturation currents of diode 1 and diode 2, respectively, V_{T1} and V_{T2} are the thermal voltages of respective diodes, a_1 and a_2 represent the diode ideality constants.

For the two-diode model, several researchers have calculated the values of I_{o1} and I_{o2} using iteration. The iteration approach greatly increases the computation time, primarily due to the unsuitable values of the initial conditions. In general, I_{o2} is 3–7 orders of magnitude larger than I_{o1} [14].

Although researchers avoid tackling this model, due to the increased number of unknown parameters which imply an increased complexity in the computation of these parameters, however, the accuracy achieved by this model force the researchers to focus on it [8, 10, 17, 18]. Many attempts have been made to reduce the number of unknown parameters and the computational time for the two-diode model. While going through the literature, it is clearly noticed that most of the research is directed to the single diode model [6, 9, 19] due to its simplicity and less number of unknown parameters, which make it easier to analyze and extract the unknown parameters from it. Alternatively, it can be seen that the single diode model suffers from inaccuracy when exposed to weather changing conditions, which make it impractical for real life implementation.

Hence the two diode model introduces itself as a proper solution to the problem of weather variation effects as shown in Fig. 6. However the increased number of unknown parameters and the computational time hinder this model from being widely used compared to the single diode model. Alternatively the noticeable accuracy achieved by this model compared with the single diode model; make it worth the effort done by researchers to solve the issues mentioned above.

I. RESULTS AND DISCUSSION

Two m-files were written in MATLAB to simulate the single diode model (R_P-model), and the two diode model behaviors under Standard Test Conditions (irradiance = 1000 W/m^2, temperature = 25 °C). The experimental data are collected from the manufacturer's datasheet and from [16]. Two different modules are used for comparison. The specifications for both modules are summarized in Table 1. Table 2 shows the parameters calculated using both of single-diode model [2], and two-diode model [6], in addition to the execution time for each model.

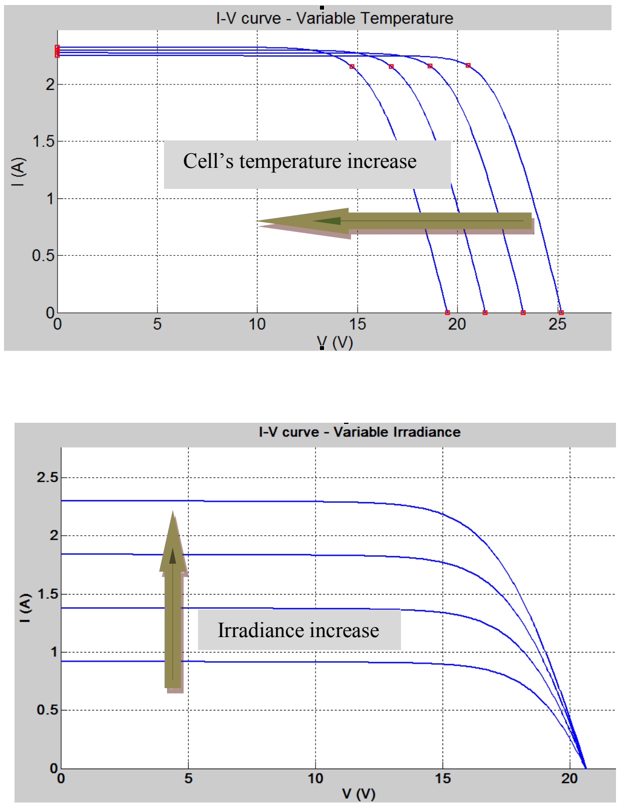

Figure 6. Effect of T & G variation on I-V curves

TABLE 1.
Specifications of the modules used in the experiment

Parameters	Shell S36	Shell ST40	Shell SP-70
I_{sc} (A)	2.3	2.68	4.7
V_{oc} (V)	21.4	23.3	21.4
I_{mp} (A)	2.18	2.41	4.25
V_{mp} (V)	16.5	16.6	16.5
K_V (mV/°C)	-76	-100	-76
K_i (mA/°C)	1	0.35	2
N_s	36	36	36

TABLE 2.
Parameters for the single-diode model and two-diode model

	Shell ST40		Shell SP-70		Shell S36	
	Single-diode model	Two-diode model	Single-diode model	Two-diode model	Single-diode model	Two-diode model
I_{sc} (A)	2.68	2.68	4.701	4.701	2.30	2.30
V_{oc} (V)	23.3	23.3	21.4	21.4	21.40	21.4
I_{mp} (A)	2.4	2.4	4.255	4.255	2.163	2.163
V_{mp} (V)	16.659	16.659	16.478	16.478	16.557	16.635
I_{o1}/I_o (A)	1.004e-8	2.94e-11	8.463e-8	3.998e-10	2.052e-10	2.055e-10
I_{o2} (A)	----	2.94e-11	----	3.998e-10	2.30	2.3
I_{pv} (A)	2.694	2.708	4.715	4.73	1.0	1.15
R_s (Ω)	1.534	1.717	0.41	0.53	1.00	0.98
R_p (Ω)	294	159	133.08	86.77	2992.131	6221.195
Average computation time (ms)	2535	3320	78	112	122	137

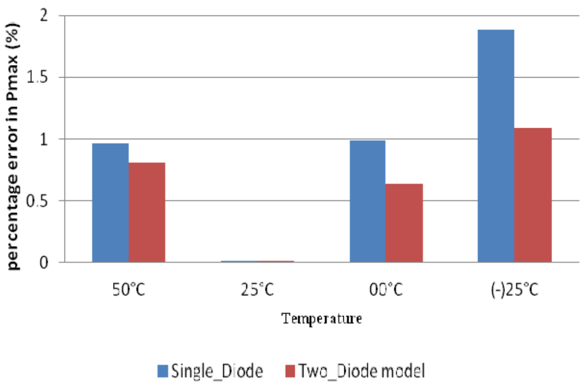

Figure 7. Error in *Pmax* (%)_ST40

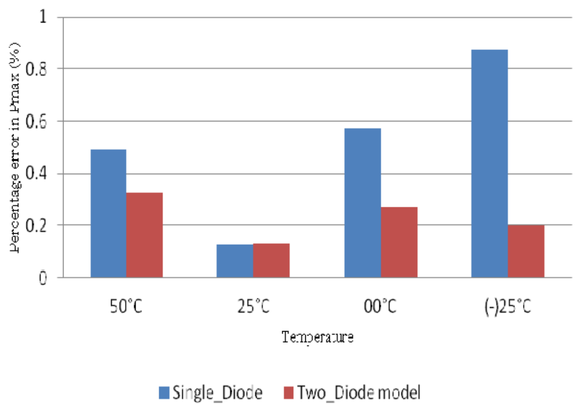

Figure 8. Error in *Pmax* (%)_SP_70

From Table 2, it is clear that the single-diode model has the advantage of less number of unknown parameters plus the shorter computation time, under STC, compared to the two-diode model.

On the other hand, both models produce almost the same values at STC as the effect of temperature variation is not included yet.

After conducting the above simulation, the effect of temperature variation was introduced to both models for the same solar modules. Fig. 7 & 8 shows a comparison between both models in terms of accuracy in calculating the maximum power point, under variable temperature (T= [-25 0 25 50], G = 1000W/m^2). It can be clearly seen from Fig. 7 and Fig. 8, that the two-diode model gives a better accuracy under temperature variation, with respect to the single-diode model. This is obvious as the single diode models were built on the assumption of the absence of the recombination losses in the depletion region, which is not practical in real solar cell, as this loss is significant especially at low voltages.

I. CONCLUSION

A comparison between single-diode model and two-diode model, in terms of accuracy and computation time, under STC and variable temperature, was held. The comparison shows that both of the models have the same ability to extract the unknown parameter and although the single-diode model has less computation time and less number of unknown parameters, the two-diode model has the superiority of keeping its accuracy much better than single-diode model under variable temperature.

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