Modeling of Solar Photovoltaic System Using MATLAB/Simulink

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***Abstract*—This work presents a Simulink-based model of a photovoltaic (PV) system using a single-diode and two-diode model of solar cell. A comparison between the two-diode and single-diode model of PV cell has been illustrated. In addition, the output of series-parallel connection of PV cells has been examined. In the model, series and shunt resistances are calculated by an efficient iteration method based on open-circuit voltage, short-circuit current and irradiance values. The PV module implemented in Simulink/MATLAB considers five parameters. The parameters are series and shunt resistance, reverse saturation current, photocurrent and ideality factor. Approximate parameters are obtained from the manufacturer`s datasheets. The model includes light intensity and ambient temperature as input. Power, cell temperature and voltage as well as any measurements of interests are the outputs. For the grid connection of solar cell, inverter, filter and a step-up transformer is utilized. The performance of the model is found satisfactory.**

Keywords—Irradiance; Temperature; Resistance; Series-parallel; Solar PV.

I. INTRODUCTION

The renewable energy sources are playing an important role in power systems and the use of solar energy is increasing day by day. Solar power is generated using solar photovoltaic (PV) arrays and electric inverter. A PV array is formed by series/parallel combination of PV solar modules [1]. The output power generated from the solar panels is intermittent in nature and varies with the irradiance level, temperature, different orientations, panel aging, and so on [1-3]. A PV system is the most cost effective and environment friendly in many applications especially in isolated areas [4].

This work demonstrates the basic combination of PV array and discusses different output characteristics of PV array in various conditions such as irradiance change, temperature variations and different internal resistance to demonstrate the various effects for series-parallel PV array. In this paper, modeling of a PV cell based on the Shockley diode equation in MATLAB [5-7] is discussed. A comparison between the single-diode and two-diode model of PV cell has also been illustrated. Overall, a detail model of PV cell with inverter, filter, and step-up transformer has been designed in this work.

II. BASIC OF PV CELL

A. *Operating Principle*

A PV cell produces current when sun light is irradiated upon on it and produces electron-hole pair as PV cell materials absorb photons having energy exceeding the band-gap of the material [8]. These generated carriers are swept apart by the internal electric fields of this cell and they contribute to current if the cell is connected with external circuit.

B. *Equivalent Circuit of a PV Cell*

A solar cell can be represented by a widely accepted equivalent circuit shown in Fig. 1 and 2 [8].

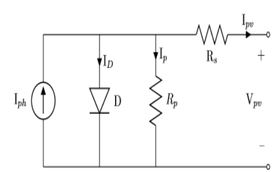

Figure 1 Single diode circuit.

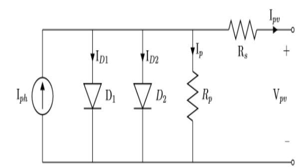

Figure 2 Two diode circuit

When the cell is exposed to light, direct current is generated that varies linearly with solar radiation. The model can be improved by including the effects of a shunt resistance (R_P) and another in series (Rs) [9]. Here, R_s is introduced for considering the voltage drops and internal losses due to flow of current and R_p takes into account the leakage current to the ground when the diode is reverse biased.

C. *Comparison Between Single and Two Diode Model*

The two-diode model takes into account the effect of recombination between electron-hole pair. In it, the number of equations as well as unknown parameters increases, thereby making calculations little bit more complex but gives more accurate results as compared to the single-diode model. Considering mathematical computations and number of iterations, computational errors are less in the single-diode model and it is faster than two-diode model due to less complex equations [9].

III. BASIC SIMULINK MODEL OF PV CELL

The fundamental equation of PV cell can be derived from the theory of Shockley diode equation and semiconductor theory [10]. The single diode Simulink model is given in Fig. 3. The fundamental equations [5] needed to design a PV cell are given below:

Using KCL in Fig. 1 we get

$$I_{PV} = I_{Ph} - I_D - I_P \tag{1}$$

As we know Shockley diode equation

$$I_D = I_0\left[\exp\left(\frac{e\left(V_p + R_s I\right)}{nk_B T}\right) - 1\right] \tag{2}$$

Now putting this value into equation (1) we get

$$I_{PV} = I_{ph} - I_0\left[\exp\left(\frac{e\left(V_p + R_s I\right)}{nk_B T}\right) - 1\right] - I_P \tag{3}$$

Finally, putting the value of I_P in equation (3) from Fig. 1

$$I_{PV} = I_{ph} - I_0\left[\exp\left(\frac{e\left(V_p + R_s I\right)}{nk_B T}\right) - 1\right] - \frac{V_p + R_s I}{R_p} \tag{4}$$

Now the output current at the standard test conditions (STC) is given as [5]:

$$I_{PV} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_p}{a_{ref}}\right) - 1\right] \tag{5}$$

If we consider short circuit condition, V=0 we get

$$I_{sc,ref} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{0}{a_{ref}}\right) - 1\right] = I_{ph,ref} \tag{6}$$

But photo current depends on light intensity and temperature. Therefore, equation of photocurrent may be defined as

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{ph,ref} + \mu_{sc}.\Delta T\right) \tag{7}$$

Where, G=Irradiance, G_{ref} =Irradiance at STC, $\Delta T = T_c - T_{ref}$ (Kelvin), T_{ref} =Cell temperature at STC = 25 + 273 = 298, μ_{sc}: Coefficient temperature of short circuit current (A/K), provided by the manufacturer, $I_{ph,ref}$: Photocurrent (A) at STC.

Finally, by simplification we get reverse saturation current

$$I_0 = I_{0,ref}\left(\frac{T_c}{T_{ref}}\right)^3 \exp\left[\frac{-q\Sigma_G}{A.K}\right]\left(\frac{1}{T_c} - \frac{1}{T_{ref}}\right) \tag{8}$$

In order to design this model more accurately, R_s and R_p are calculated using Newton-Raphson method in order to get maximum power from the cell. Now, for findings R_s and R_p at STC

$$I_{mp,ref} = \frac{P_{mp,ref}}{V_{mp,ref}} = I_{ph,ref} - I_{0,ref}\left[\exp\left(\frac{V_{mp,ref} + I_{mp,ref}.R_s}{a}\right) - 1\right] \tag{9}$$

Putting the value of I_0 and $I_{ph,ref}$ finally we get

$$R_p = \frac{V_{mp,ref} + I_{mp,ref}.R_s}{I_{sc,ref} - I_{sc,ref}\exp B + I_{sc,ref}\exp\left(\frac{V_{0c,ref}}{a}\right) - \frac{P_{mp,ref}}{V_{mp,ref}}} \tag{10}$$

Where, B= $\dfrac{V_{mp,ref} + I_{mp,ref}.R_s - V_{0,ref}}{a}$, $a = \dfrac{N_s.A.K.T_c}{q}$

IV. SIMULATION RESULT

A. *Effect of different irradiance on a single PV cell*

Figures 4 and 5 show the effect of variation of solar irradiance on the I-V and P-V curves. As the irradiance decreases, photo current (Iph) also decreases. The photo current varies linearly with irradiance level. From Fig. 4, it is observed that photo current is 3.11A when irradiance is 1000 W/m^2 and 0.7 A when irradiance is 200 W/m^2. From Fig. 5, it is observed that the output power decreases when irradiance decreases. It is found that when irradiance is 1000w/m^2 power is 49.3 W but for other values of irradiance output decreases. .

B. *Effect of different temperature on a single PV cell*

Figures 6 and 7 demonstrate the effect of the ambient temperature on the P-V and I-V characteristics. It can be noted from Fig. 6 that maximum power output decreases with increasing temperature. In this model, the temperature is varied from 25 $^\circ C$ to 500 $^\circ C$. From Fig. 6, maximum power output is 49.3 W and 18 W when temperature is 25 $^\circ C$ and 500 $^\circ C$, respectively. In Fig. 7, it is observed that the output voltage decreases from 23.5V to 19.1V as the temperature is increased from 25 $^\circ C$ to 500 $^\circ C$, respectively.

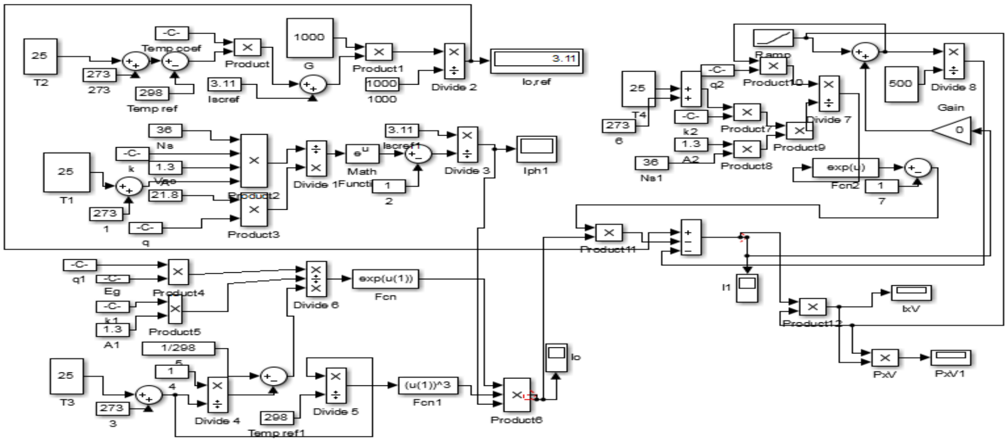

Figure 3 Simulink model of a single diode PV cell

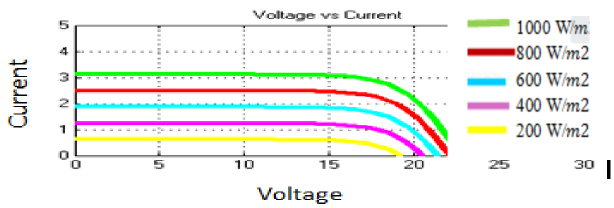

Figure 4 Irradiance effect on I-V curve

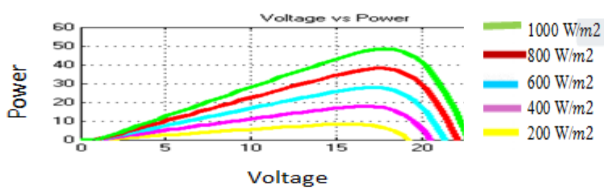

Figure 5 Irradiance effect on P-V curve

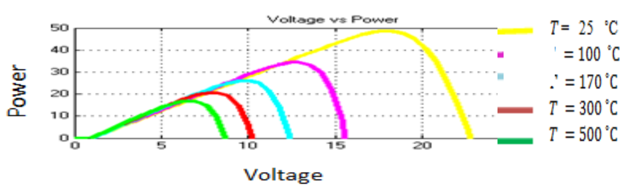

Figure 6 Temperature effect on P-V

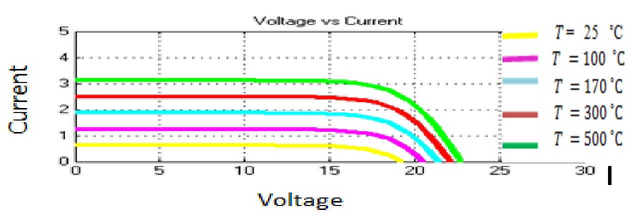

Figure 7 Temperature Effect on I-V

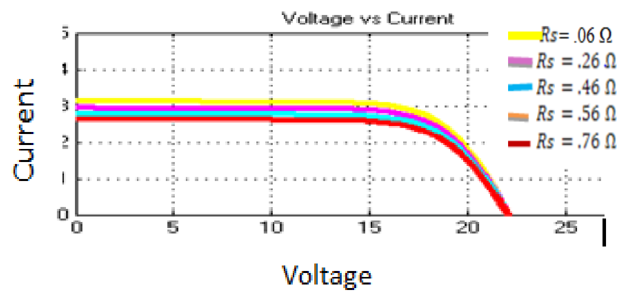

Figure 8 Rs effect on I-V curve

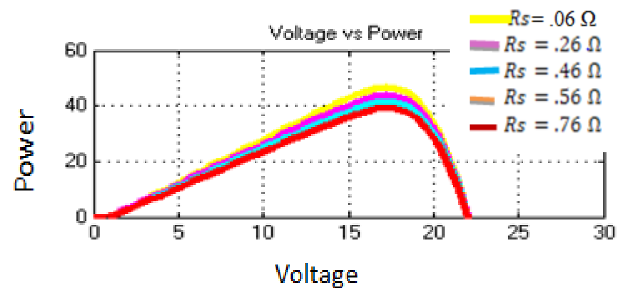

Figure 9 Rs effect on P-V curve

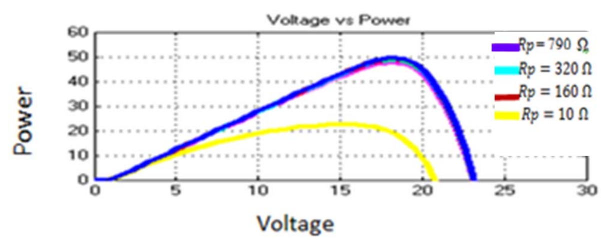

Figure 10 Rp effect on P-V curve

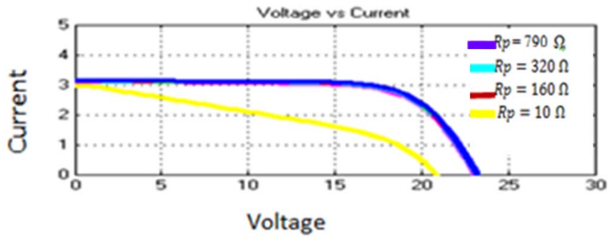

Figure 11 Rp effect on I-V curve

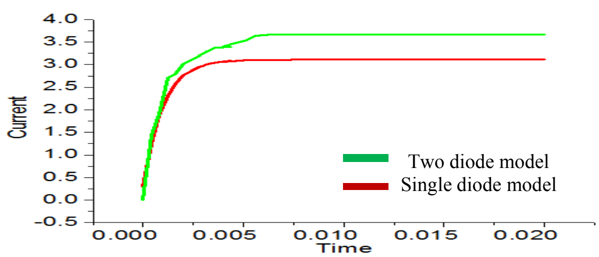

Figure 12 Current vs. Time

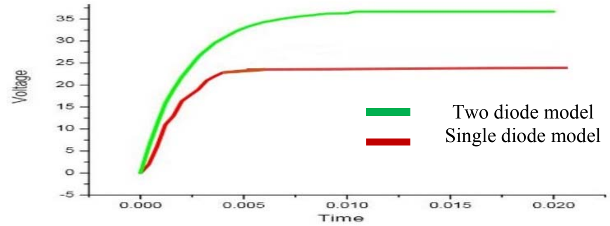

Figure 13 Voltage vs. Time

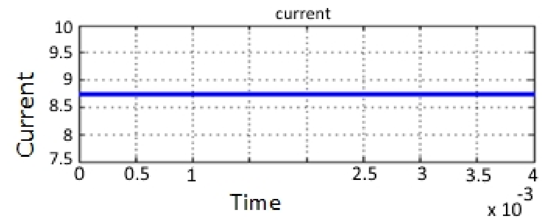

Figure 15 Output current vs. Time for series-parallel connection

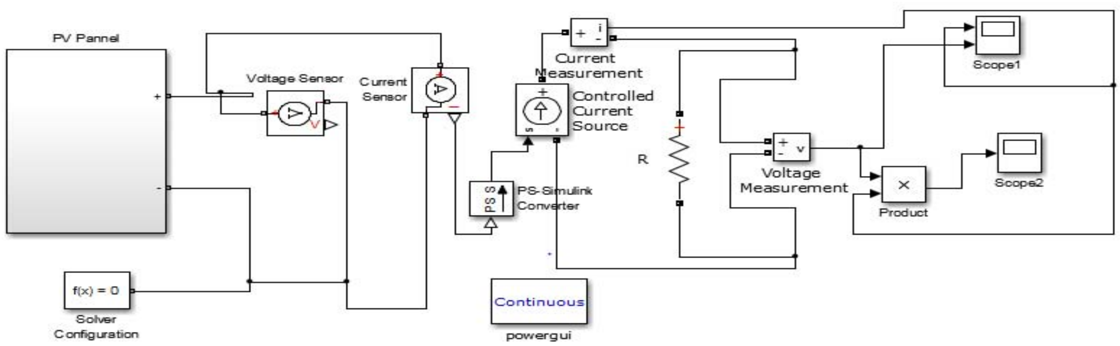

Figure 14 Series- parallel connection of PV cell

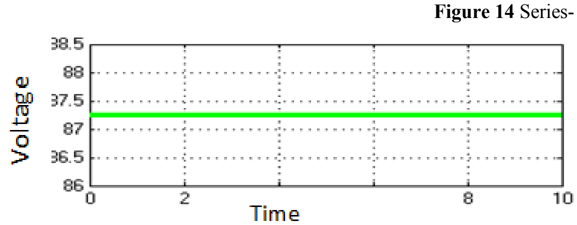

Figure 16 Output Voltage vs. Time for series-parallel connection

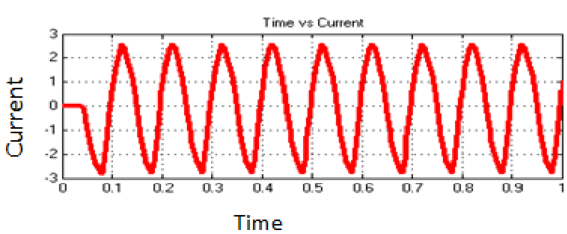

Figure 17 Current vs. Time after filtering

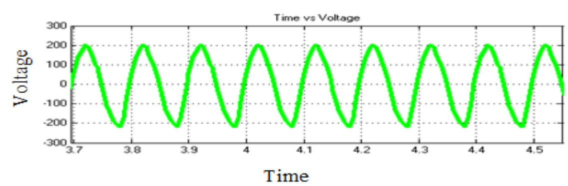

Figure 18 Voltage vs. Time after filtering

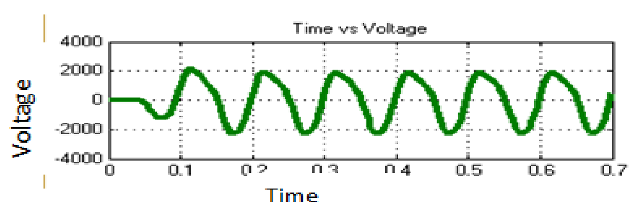

Figure 19 Voltage vs. Time after 220V/2200V step-up transformer

C. *Effect of different Rs and Rp on a single PV cell*

Figures 8 and 9 demonstrate the effect of variation of the series resistance and parallel resistance on the output of solar cell. The higher the value of the series resistance, the lower the output current as well as the maximum power. It is also found that a lower value of parallel resistance decreases output power. Therefore, suitable values of Rs (Rs=0.56 Ω) and Rp (Rp=790 Ω) have been calculated by Newton Raphson iteration method that gives more accurate result at maximum power point [5]. From Fig. 8, it is observed that photo current decreases from 3.11A to 2.6A as series resistance is varied from 0.06 Ω to 0.76 Ω. Also, the output power increases from 21W to 49.3W as the parallel resistance is varied from 10 Ω to 790 Ω. The effects of parallel resistance on P-V and I-V curves are shown in Fig. 10 and 11, respectively. Table I shows the simulation result where for the same approximation method, we got 49.3W whereas manufacture's got 49W experimentally.

TABLE I. PWX 500 PV MODULE (49W) CHARACTERISTICS [5]

Name (Unit)	Experimental Values	Simulated Values (single diode)
P_{mp} (W)	49 W	49.3 W
V_{mp} (V)	17 V	17.2 V
I_{mp} (A)	2.88 A	2.9 A
V_{oc} (V)	21.6 V	23.5 V
I_{sc} (A)	3.11 A	3.11 A

D. *Simulation Result of simulated single diode and built-in two diode model in MATLAB*

Figures 12 & 13 demonstrate the comparison between two-diode and single-diode model. Figure 12 shows that the output current of the built-in two-diode model in MATLAB is 3.67A whereas the output current of the simulated single-diode model is 3.11A. From Fig. 13, it is seen that output voltage of built in two-diode model is 36.7V which is greater than the output voltage 23.5V of simulated single-diode model.

E. *Simulink Model of Series- Parallel Connection of MATLAB built-in PV Cell*

The output current, voltage and power of a single solar cell is very low. For getting desired output power solar array is created by connecting solar cells in series and parallel. Figure 14 shows the Simulink model of a series parallel connection which contains six series and six parallel combinations of solar cell. It is noted from Fig. 15 that the output current increases from 1.5A (built in single cell) to 8.75A (six cells are parallel). Also, the output voltage increases from 15.3V (built in single cell) to 87.67V (six cell are series) as shown in Fig. 16.

F. *Result of DC to AC Conversion*

Solar cells produce power at low voltages. Stepping up DC voltage is a difficult task. It is likely to be more energy efficient to convert it to AC and step it up before transmission [11]. The outputs of current and voltage are shown in Fig. 17 & 18. In this study, a single phase pulse width modulation (PWM) inverter has been used. Harmonics are generated in inversion process. Therefore, to reduce harmonics, a first order low pass filter has been used. In Fig. 17 current is found 2.7A and in Fig. 18, the voltage is found 210V without any harmonics.

G. *Simulated result of Step-up Transformer*

Transformers are used to step up the output voltage of the inverter. In this model, a single phase PWM inverter, a step up three phase two winding 100kVA, 220V/2200V transformer is used. The output voltage 210V is stepped up to approximately 2000V using step up transformer which is shown in Fig. 19.

V. CONCLUSION

The performance of a solar cell depends primarily on weather conditions. The field tests to examine the performance of solar cells are highly expensive. However, a detailed simulation study can save both time and resources. The implemented PV model using MATLAB/Simulink covers all these concerns. The Simulink implementation of PV model takes into account five parameters. The effects of variations of model parameters and the effects of different solar light intensity (200-1000 w/m^2) and ambient temperature (25-500˚C) have been demonstrated. The PV model can be automatically modified to simulate configurations ranging from a single PV cell to a string of modules. The comparison of MATLAB built in single diode and two diode model cell has been demonstrated. The manufacturer's test of PWX 500 PV module gives 4.89% efficiency whereas the simulated model has given 4.98% efficiency. Therefore, it can be concluded that the proposed model has given slightly higher efficiency than the manufacturer's value. Series and parallel combinations of cells for getting desired output are designed and simulated. Finally, it can be concluded that the complete model with the inverter and transformer shows satisfactory performance.

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