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SIMULATING THE ELECTRICAL CHARACTERISTICS OF A PHOTOVOLTAIC CELL BASED ON A SINGLE-DIODE EQUIVALENT CIRCUIT MODEL

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Abstract—This research work presents the simulation based study of a commercial solar cell for analyzing the real-time behavior of a PV module. The mathematical modelling is based on Equivalent circuit of the solar cell and demonstrating the practical approach for using the single diode five parameters (IM5P) mechanism. This research involves purely mathematical formulation to extract the unknown parameters of PV cell by applying the Lambert W function. The I – V and P – V characteristics are emulated under different temperature and radiation levels by using the Linear Technology's LTSpice simulator.

Keywords— Energy Harvesting, I – V & P – V Curve, Solar Equivalent Circuit, Lambert W function.

I. INTRODUCTION

THE world is facing huge energy crises and we will run out of fuel coal and gases by 2071 as it is predicted by CIA (Central Intelligence Agency) [1].This is an alarming situation which emphasizes the researchers and scientists around the globe to make alternative possible solutions. Energy harvesting is the only hope to overcome this issue, however, renewable energy sources can be utilized to tackle most of the energy hungry devices whether it is in form of a large-scale applications like solar systems power generators or a small scale domestic use like cell phone, Ipods, and wireless sensor networks, elaborated in a recent review by A. S. Adila, A. Husam, J. H. Sana G. Husi [2]. The most viable source which can equip greener ways successfully since last decade is solar energy.

The Photovoltaic market have seen rapid growth for solar power systems that entertains the possible gap of renewable energy interpretation for both macro and micro systems as reported in Ren21 [3]. A Photovoltaic system converts the sunlight directly into electricity and the main device is solar cell in the system. Solar cell arrays are formed by grouping them together. The electronic converters play a viable role for processing the electricity from the PV system as defined by M. G. Villalva, J. R. Gazoli, E. R. Filho [4]. A solar cell is made of semiconductor diode which is exposed to light and consists of various types of semiconductors using different manufacturing processes as reviewed by A. S. Sedra, K. C. Smith [5]. M.A. Eltawil, Z. Zhao discussed that the incoming solar radiations and the intrinsic properties are responsible for the electric energy generation in a solar cell [6]. The solar radiation is composed of photons of various energies, some of them are absorbed at p-n junction as shown in Fig 1., described in Union of Concerned Scientists [7]. If the photons with energies are lower than the bandgap of the solar cell, they are useless and will not generate electric current or voltage. Whereas, photons with energy higher than the bandgap will generate electricity and the energy corresponding to the bandgap will be used only. The remaining energy is dissipated as heat in the body of solar cell as mentioned by J. Bikaneria, S. P. Joshi, A. R. Joshi [8].

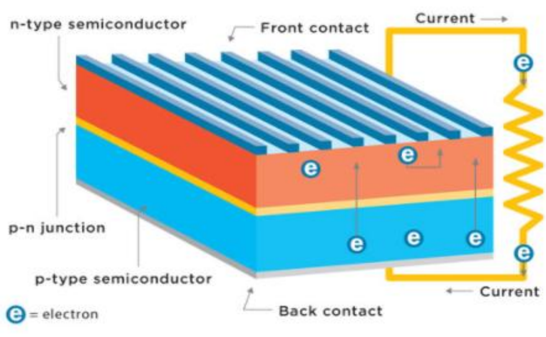

Fig 1. Schematic diagram demonstrating the operation of p-n junction of a Solar Cell

Despite of widely adopted renewable solar solution, there's still lack of understanding the performance efficiency and power extraction, when it comes to the selection of solar panels or arrays by the end users. Many mathematical models are highlighted for demonstrating the non-linear response of a PV system as highlight by E. M. G. Rodrigues, R. Melicio, V. M. F. Mendes and J. P. S. Catalao [9]. The common technique is to model the solar equivalent circuit and amongst all possible parametric models, the single diode model is the popular one, which is also known as 1M5P (Single Mechanism, Five Parameters). It is used to predict the real-time behavior of a solar cell mentioned by Yetayew and Jyothsna [10]. For I – V and P – V characteristics, the complicated procedure is required which involves certain equations and calculations. The solar cell involves non-linear and exponential expressions that results the equations as implicit, which is complicated, iterative, and time consuming. J. Cubas, S. Pindado, C. D. Manuel [11] demonstrated in their research that the explicit technique is required which consists of analytical formulation with use of Lambert W function for making the parametric model simpler. In this paper, the single diode equivalent circuit is being modelled for a commercial solar cell for obtaining the unknown parameters from the manufacturer's datasheet. Matlab is used for the formulation of the explicit expressions whereas, the LTSpice circuit simulator is used to model and simulate the performance of solar cell by demonstrating the I – V and P – V curves at temperature and irradiations variations of solar equivalent circuit.

II. Modelling Of Solar Cell

A. *Ideal Single Diode Model for Photovoltaic Cell*

The photovoltaic technology is based on the principle of electron hole creation in each cell that consists of two different layers; p type and n type. However, The I - V curve characteristics of a solar cell are like the exponential characteristics of the ideal diode as described by Walker [12]. To understand the phenomenon of any solar cell, panel or an array, it is needed to derive the electrical parameters of PV cell in to the equivalent circuit as a necessary requirement. As shown in the Fig. 2, the ideal solar cell consists of current source I_L, which is parallel to the diode I_D. The model containing 3 parameters also known as 1M3P (Single mechanism three parameters) suggested by M. Azzouzi, D. Popescu and M. Bouchahdane [13].

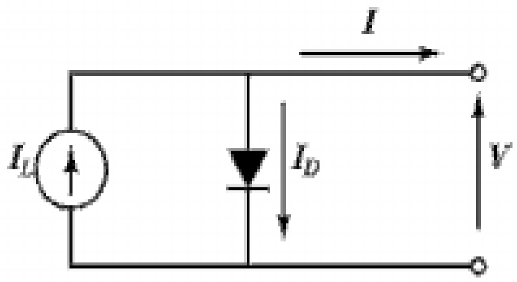

Fig. 2. Ideal Single Diode Model (1M3P)

Therefore, the equation can be derived by using the Kirchhoff's law:

$$\mathbf{I = I_L - I_D} \qquad \mathbf{(1)}$$

Where I_D equals to,

$$\mathbf{I_D = I_O \left[\exp\left(\frac{V}{AV_T}\right) - 1\right]}$$

The output current is represented by the following non-linear I – V equation:

$$\mathbf{I = I_L - I_O \left[\exp\left(\frac{V}{AV_T}\right) - 1\right]} \qquad \mathbf{(2)}$$

However, this model does not be able to produce accurate results for modelling I – V and P – V curves of a solar cell.

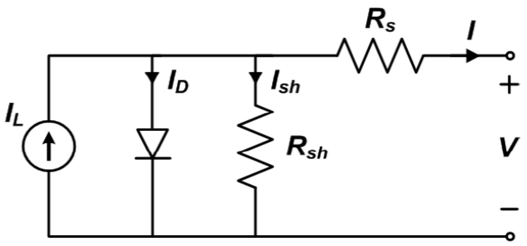

Fig. 3 Single Diode Equivalent Circuit (1M5P)

B. *Single Diode Model with Series and Shunt Resistors*

To specify the most popular and practical functioning of a solar cell, M. Wolf and H. Rauschenbach [14] denoted the representation of losses by the resistors as shown in the Fig. 3, having a current source connected in parallel with a diode and two resistors, one in series and other in parallel.

Azzouzi, Popescu and Bouchahdane [13] also mentioned that this model composed of five parameters for which it known as 1M5P (Single mechanism, five parameters), as current, voltage, and power curves can be easily deduced by this model by calculating the five unknown parameters. Mostly the short circuit, open circuit and maximum power points are included in the datasheet of solar cells as illustrated in Fig. 4.

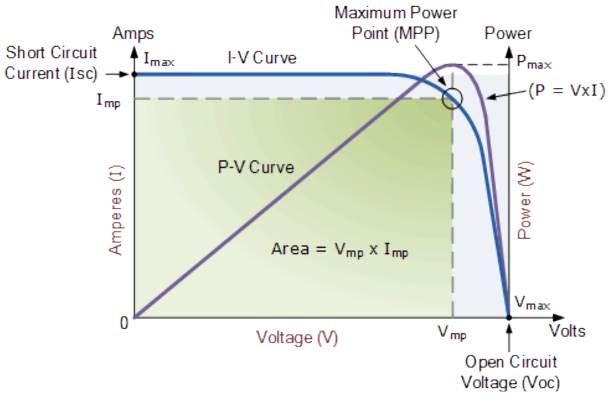

Fig. 4. I – V and P – V characteristics of a typical solar cell

III. Mathmatical Modeling Of Single Diode Equivalent Circuit

A. Wafaa, A. M. Ashraf, A. Fouad, S. Saad [15] described that it is important to derive the characteristics equations for solar cell for calculating the five-parameters of an equivalent solar circuit. Considering the Fig. 3, the equation is given as:

$$I = I_L - I_D - I_{sh} \qquad (3)$$

To fully define the relationship between the output current of photovoltaic cell and the terminal voltage for the single diode model is given by the following equation:

$$I = I_L - I_o\left[\exp\left(\frac{V+IR_s}{aV_T}\right) - 1\right] - \frac{V+IR_s}{R_{sh}} \qquad (4)$$

Along with Thermal Voltage; $V_T = n\frac{KT}{q}$ [V]

Where I_L denotes the current generated by the incidence of light, I_D denotes the diode current, R_S represents the series resistance, for leakage current R_{sh} is denoted as Shunt resistor, ***a*** is the ideality factor, ***Vt*** is the thermal voltage, ***q*** as an electron charge, the Boltzman constant ***K***; the ***n*** as number of cells in series and ***T*** as the temperature.

Solar cell is required to be characterized by the short circuit current ***Isc***, the open circuit voltage ***Voc***, and ideality factor ***a***. Equation (4) can be rewritten as:

Short Circuit current: I = Isc, for V=0

$$I_{sc} = I_L - I_o\left[\exp\left(\frac{I_{sc}R_s}{aV_T}\right) - 1\right] - \frac{I_{sc}R_s}{R_{sh}} \qquad (5)$$

Open circuit Voltage: I = 0 for V = Voc

$$0 = I_L - I_o\left[\exp\left(\frac{V_{oc}}{aV_T}\right) - 1\right] - \frac{V_{oc}}{R_{sh}} \qquad (6)$$

Maximum power point equation: I = Imp, for V = Vmp

$$I_{mp} = I_L - I_o\left[\exp\left(\frac{V_{mp}+I_{mp}R_s}{aV_T}\right) - 1\right] - \frac{V_{mp}+I_{mp}R_s}{R_{sh}} \qquad (7)$$

A. Required Equations for Calculating Unknown Parameters

In order to obtain the value of series resistor, it is need to calculate the implicit expression, which is unstable and time consuming at the same time, for the sake of making expression decoupled, analytical formulation is required to make it explicit. Therefore, the implicit current - voltage expression is converted as an explicit one by applying the technique to solve the voltage as a function of current and vice versa, it is intended to make use of popular strategy as suggested by J. Amit, S. Sandeep, K. Avinashi [16], Villegas [17], K. Roberts, S. R. Valluri [18] that is known as Lambert W function.

For calculating ***Rs***:

$$Rs = A\left(W_{-1}(B\exp(C)) - (D + C)\right) \qquad (8)$$

Where,

$$A = \frac{aV_T}{I_{mp}}$$

$$B = -\frac{V_{mp}(2I_{mp} - I_{sc})}{V_{mp}I_{sc} + V_{oc}(I_{mp} - I_{sc})}$$

$$C = -\frac{2V_{mp} - V_{oc}}{aV_T} + \frac{(V_{mp}I_{sc} - V_{oc}I_{mp})}{(V_{mp}I_{sc} + V_{oc}(I_{mp} - I_{sc}))} \qquad (9)$$

$$D = \frac{V_{mp} - V_{oc}}{aV_T}$$

For calculating ***Rsh***:

$$R_{sh} = \frac{(V_{mp} - I_{mp}R_s)(V_{mp} - R_s(I_{sc} - I_{mp}) - aV_T)}{(V_{mp} - I_{mp}R_s)(I_{sc} - I_{mp}) - aV_T I_{mp}} \qquad (10)$$

For calculating I_0:

$$I_0 = \frac{(R_{sh} + R_s)I_{sc} - V_{oc}}{R_{sh}\exp\left(\frac{V_{oc}}{aV_T}\right)} \qquad (11)$$

For calculating I_L:

$$I_L = \frac{R_{sh} + R_s}{R_{sh}} I_{sc} \qquad (12)$$

IV. Methodology

A. Parameter Identification and Calculation from Manufacturer's Datasheet

In order to evaluate the unknown parameters (I_L, I_O, Rs, Rsh) and to simplify the calculations for specific model, P. M. Cuce, E. Cuce [19] elaborated that the ideality factor should be considered as generic value which is suggested for monocrystalline cell type as a = 1.2 and is independent of any temperature and irradiation. The following procedure is followed for calculating the parameters from manufacturer's datasheet.

1) *Approximating the ideality factor **a** as 1.2 for Monocrystalline Cell*
2) *Calculating the Series Resistance **Rs** with Equation (8)*
*Calculating the Shunt Resistance **Rsh** with Equation (10)*
3) *Calculating the Saturation Current I_O with Equation (11)*
4) *Calculating the Photodiode Current I_L with Equation (12)*

The electrical characteristics are given in the TABLE I, which demonstrates the perquisite data for insertion in to the expressions. The input parameters from the datasheet at (STC) Standard Test Conditions are 1000 W/m2 incident normal radiance, Cell temperature is 25 ^{0}C and Air Mass AM1.5g.

TABLE I
Electrical Specifications Of iXolar SolarMD SLMD481H08L

I – V Curve Characteristics	Specifications	Units
Open Circuit Voltage (Voc)	5.04	V
Short Circuit Current (Isc)	0.2	A
Voltage at maximum power point (Vmpp)	4.0	V
Current at maximum power point (Impp)	0.178	A
Maximum Peak Power (Pmpp)	0.714	W
Temperature Coefficients of Isc (alpha)	0.12	mA/(cm^2) K
Temperature Coefficient of Voc (beta)	-2.1	mV/K

The obtained parameters are demonstrated in TABLE II, where the unknown parameters have been calculated by the defined equations and pushing the ideality factor as constant and independent.

TABLE II
Calculated Parameters of iXolar SolarMD SLMD481H08L

Parameters	Calculated Values
I_0	9.0837e-10
I_L	0.2009
Rs	1.7795
Rsh	398.4280
a	1.2

B. Simulating the Solar Equivalent Circuit

In this paper, the commercial solar cell iXolar SolarMD SLMD481H08L [20] is being selected for analyzing I – V and P – V curves based on mathematical formulation and using the Linear Technology's LTSpice (Linear Technology Simulation Program with Integrated Circuit Emphasis) software. However, the obtained values will be modelled on the solar equivalent circuit for evolving the behavior of solar module on simulator. As defined in section IV. A, the input parameters have been calculated for modelling and simulation purpose for solar equivalent circuit as shown in Fig. 5.

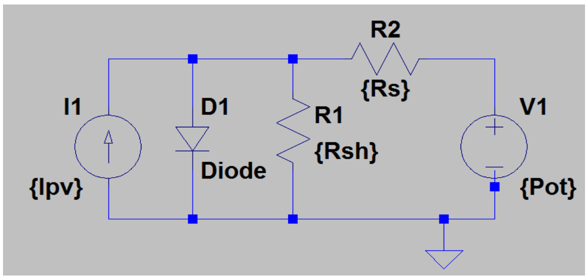

Fig. 5 Single diode Equivalent circuit for iXolar SolarMD SLMD481H08L

V. Results and Discussions

A. I – V and P – V curve simulation

The generated I – V and P – V curve for commercial solar cell has been plotted as demonstrated in Fig. 6 and Fig. 7. The simulations are mathematically formulated based on the datasheet information. These plots are being further simulated based on two variations for solar equivalent circuit. The environment dependence has been modelled to analyze the PV cell response and the characteristics points to adequate the output performance of the cell. For this purpose, the temperature and irradiations levels are adopted to configure the system response in the real-time environment.

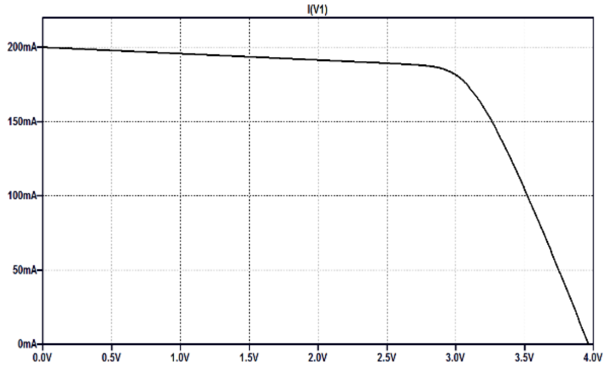

Fig. 6. I – V curve of Solar Equivalent Circuit of iXolar SolarMD SLMD481H08L

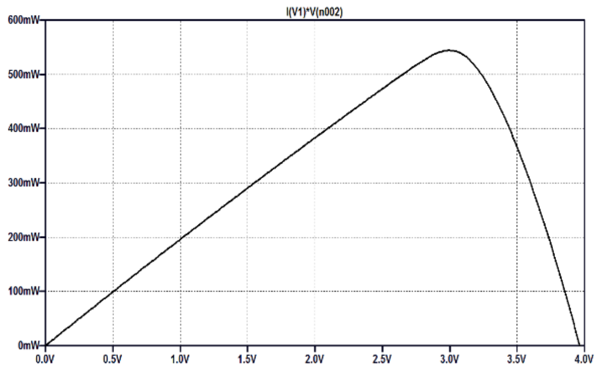

Fig. 7. P – V curve of Solar Equivalent Circuit of iXolar SolarMD SLMD481H08L

B. Effect of solar irradiation on I – V curve

The simulation is being performed on the same solar circuit for different levels of solar irradiation, which varies from 200 W/m^2 to 1000 W/m^2 by maintaining the temperature constant at 25 ^{o}C. It can be seen in Fig. 8, that the generated current depends on the incident light, as long as the irradiation is increasing the current also increases. As there is slight change of voltage with respect to the increment of the current.

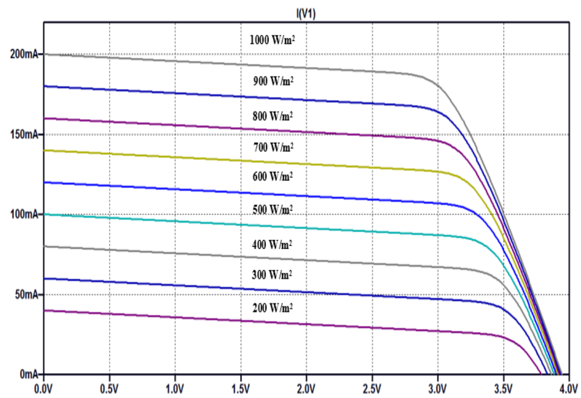

Fig. 8. Solar Irradiation levels from 200 W/m^2 to 1000 W/m^2 at 25 ^{0}C

C. Effect of temperature on I – V and P – V curve.

In this simulation, the temperature is being varied from 15 ^{0}C to 85 ^{0}C and keeping the irradiation level constant at 1000 W/m^2. Fig. 9 and Fig. 10, shows the I – V and P – V curve generated on different temperature ranges. As it is clearly indicated that by varying the temperature from low to high, the voltage is being affected. Increasing the temperature causing the decreased voltage and maximum power point at the same time. While the current generated by incident light remained constant.

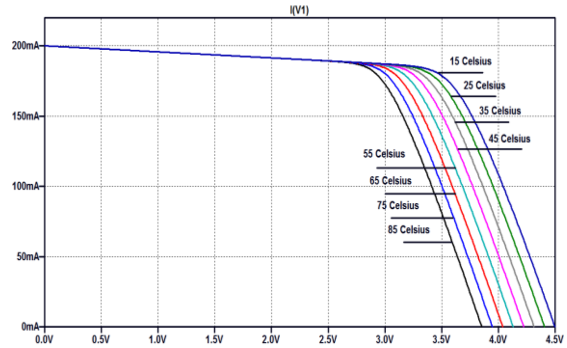

Fig. 9. I – V Characteristics for Temperature variation between 15 ^{0}C to 85 ^{0}C at 1000 W/m^2

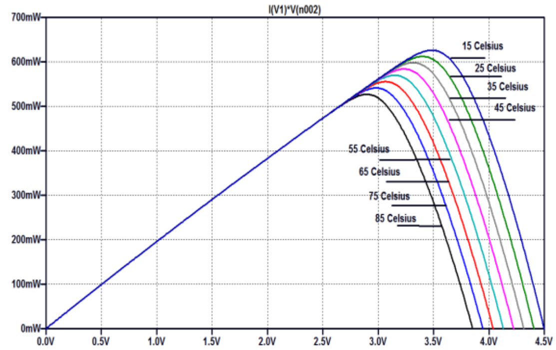

Fig. 10. P – V Characteristics for Temperature variation between 15 ^{0}C to 85 ^{0}C at 1000 W/m^2

VI. CONCLUSION

In this research work, the commercial solar cell is being examined to predict the solar cell response on the simulator based on the I – V and P – V characteristics. For such study, the solar cell is being modelled as a single diode equivalent circuit (1M5P), the only source available is the manufacturer's datasheet that is being considered to extract the unknown parameters. Certain calculation and explicit expressions have been performed to get most of the optimal values of the module. This way the calculation is being done on the Matlab software and the obtained parameters were simulated on LTSpice simulator on the equivalent circuit. The results have been analyzed on the two cases; one on the temperature variation and keeping irradiation constant and second on the irradiation levels keeping temperature constant. The plots of I -V curves indicate that as far as temperature increases the cell current slightly increases and the voltage is being decreased. It is observed that P – V characteristics of solar cell denotes the decrease in voltage as the temperature is being decreased which proportionally affects the power output of the cell. However, the increment in the irradiation levels also increases the output power. Finally, this simulation based study provides the end users to establish the realistic mathematical modelling of solar cell, panel or an array to estimate the electrical behavior of PV systems for planning their own systems.

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