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PARAMETERS EXTRACTION OF A DOUBLE-DIODE MODEL OF PHOTOVOLTAIC CELL USING NEWTON-RAPHSON METHOD

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ABSTRACT

The mathematical modeling of solar cells is essential for any optimal knowledge of the operation efficiency or diagnosis of photovoltaic cell. The photovoltaic module is generally represented by an equivalent circuit whose parameters are experimentally calculated by using the characteristic I-V. Determination of these parameters poses a challenge to researchers, manufacturers and the end-user, making the characterization of the PV module difficult. Hence, parameters extraction of double diode model of PV cell was embarked upon. Double diode model was chosen because of its better accuracy compared to the single diode model. I-V characteristics equation of the model was used as the basis upon which Newton-Raphson method was used for estimating the parameters. In this research study, parameters of a double diode model (I_{ph}, I_{o1}, I_{o2}, a_1, a_2, R_s and R_p) were found by obtaining seven different objective functions $f_1(x)$ to $f_7(x)$ and their derivatives with respect to the parameters. These derivatives of the objective functions were used to obtain the Jacobian matrix J(x). Newton-Raphson method was developed on software MATLAB/Editor to compute the parameters.

Keywords: *Photovoltaics, Double diode, Newton-Raphson, Jacobian matrix, MATLAB, Standard Test Condition.*

INTRODUCTION

Due to the limited number of stock and increasing prices of conventional energy sources such as petroleum, coal, nuclear fuels etc. and their environmental effects, there is a need for energy from renewable sources such as solar, wind, hydro, geothermal etc. for electrical power generation (Karki and Roy, 2001). Photovoltaic (PV) energy system has become most dominant among different renewable energy sources, due to the fact that it is economical, easy to maintain, no emission of gases and minimum periodic maintenance is required.

Photovoltaic (PV) is a technology in which radiant energy from the sun is converted to direct current (DC) electricity (Betka, 2004). A photovoltaic cell (PV cell) is a device that converts the energy of sunlight into electricity using the photovoltaic effect (Ravaee *et al.,* 2012). Conversion of the PV energy into electricity is by means of a PV array and a power-electronic converter system with a control mechanism. PV modules which are PV cells that are integrated and connected together in series or parallel to form an array determines the voltage and current ratings of the PV modules. Photovoltaic energy have become increasingly popular and are ideally suited for distributed systems due to the adverse effect caused by convectional energy sources like coal, petroleum etc.

Generally, PV modules are expensive. As a result, it is recommended to study their behaviour through simulation before implementation of the solar system. Single diode or two diodes are basically the equivalent circuit for simulation purpose (Pradhan, 2014). Among these circuits model, single diode has become the most widely used model as it's simple and accurate (Dezso *et al.,* 2007; Leban and Ritchie, 2008). However, the double-diode model is preferred because the current-voltage characteristic emulates that of a physical module (Ishaque and Taher, 2011). Accuracy of the parameters of a PV cell/module depends on the extraction method being used to determine the model's parameters.

Operating principles of photovoltaic cell

The PV cell operating principle is based on the photovoltaic effect (Quaschning, 2005). Photovoltaic effect is the generations of potential difference at the P-N junction, as the photons are absorbed, hole-electron pairs may be formed, when these pairs reach the P-N junction, the electric field in the depletion region pushes holes into the P-side and electrons into the N-side as shown in Fig. 1. Generally, when light is absorbed by matter, photons are given up to excite electrons to higher energy states within the material. Particularly, this occurs when the energy of the photons is higher than the forbidden band gap of the semiconductor (Green, 1998; Nelson, 2003), but the excited electrons quickly relax back to their original or ground state. In a photovoltaic device, there is an asymmetrical doping in the semiconductor which prevent the electrons from relaxing and feeds them into an external circuit. The extra energy of the excited electrons generates a potential difference or electromotive force (EMF) that drives the electrons through a load in the external circuit.

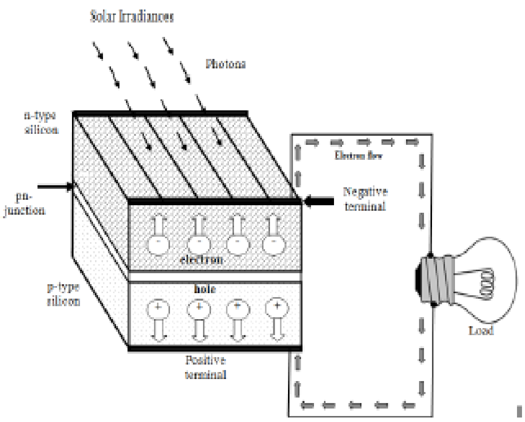

Fig. 1: PV cell (Quaschning, 2005)

Model of a PV cell

Accurate modeling of a photovoltaic cell is an important requirement for designing an efficient PV system since photovoltaic cell is the basic of a PV system (Pradhan, 2014). A number of mathematical models of PV cell are available in literature but the common ones mostly used to represent PV cell are ideal model, single-diode model and double-diode model.

(i) Ideal model

An ideal model is modeled as an ideal current source and a diode connected in parallel as shown in Fig. 2.

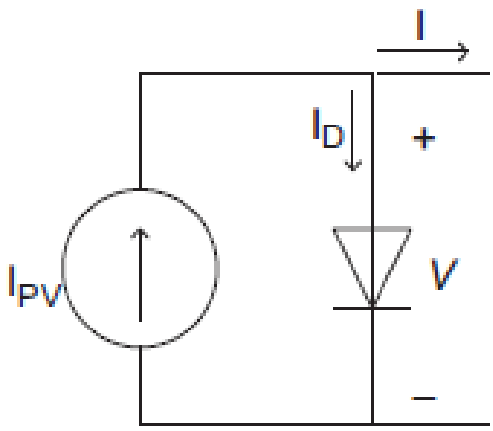

Fig. 2: Ideal PV model

Based on the Shockley theory, recombination in the space-charge zone of the diode can be ignored and as a result the second diode can be ignored (Man *et al.,* 2014). Losses due to the series and parallel resistance are ignored. Queisses diode as shown in equation (1).

$$I = I_{ph} - I_d = I_{ph} - I_o\left(e^{\frac{qV}{kT}} - 1\right)$$ ....(1)

(ii) Single diode model

Single diode model is also known as 5-p model. The five parameters from which its name was derived are The equivalent circuit is as shown in Fig. 3. The 5-p model is the widely used PV cell model as it is nearly accurate with only a small percentage error (Karamirad, 2013). Its improved accuracy lies with the inclusion of series and parallel resistance .

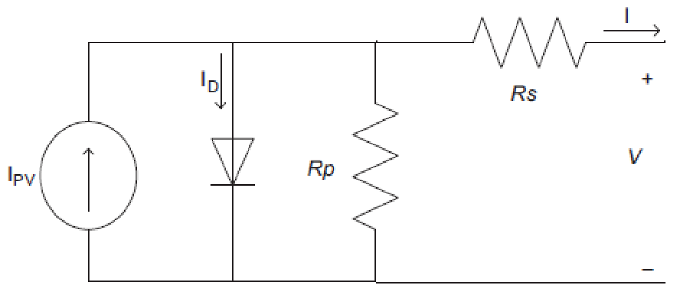

Fig. 3: The equivalent circuit of PV single diode model

Applying Kirchoff's law yield the equation (2)

$$I = I_{ph} - I_o\left(e^{\frac{V+IR_s}{aV_t}} - 1\right) - \frac{V - IR_s}{R_p}$$ ....(2)

(iii) Double diode model

The double diode model is shown in Fig. 4. It shows a second diode placed in parallel to the single diode of the 5-p model discussed above. The double-diode model characterizes the charge diffusion for the first diode and recombination for the second diode in the space charge layer (Gow and Manning, 1999).

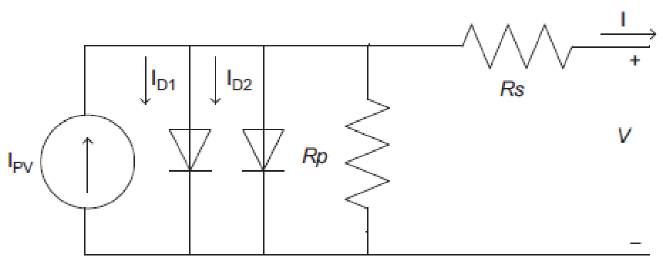

Fig. 4: The equivalent circuit of PV double diode model

The single diode and double diode model exhibit similar result for analysis purpose but the double diode model is more accurate than the single diode model at lower voltages and lower irradiance (Daniel *et al.,* 1987; Ishaque *et al.,* 2011). Behaviour of a two-diode model closely resembles that of a physical module but the model is non-linear and complex.

The use of algorithms, Levenberg/Marquardt, Newton-Raphson methods and others has simplified the calculation. The characteristic equation is given in equation (3) and modified in equation (4).

$$I = I_{ph} - I_{d1} - I_{d2} - I_p$$ ....(3)

$$I = I_{ph} - I_{01}\left(e^{\frac{V+IR_s}{a_1V_t}} - 1\right) - I_{02}\left(e^{\frac{V+IR_s}{a_2V_t}} - 1\right) - \frac{V+IR_s}{R_p}$$ ....(4)

Addition of the second diode increases the number of parameters to be computed from five to seven unknowns (I_{ph}, I_{01}, I_{01}, a_1, a_2, R_s, R_p).

Parameter extraction methods

An accurate knowledge of solar cell parameters from experimental data is of vital importance for the design of solar cells and for estimation of their performance (Bonkoungou, 2013). Thus, different solar models have been developed to describe their electrical characteristic but the electrical equivalent circuit is a convenient way in most simulation studies. Parameters of interest in the equivalent circuit are the photo-current (I_{Ph}), series resistance (R_s), diode saturation current (I_o), parallel resistance (R_p) and the ideality factor (a). In the past, several extraction methods have been proposed as reported in literature, it is found that in general these methods can be classified into three categories namely analytical method, evolutionary method and iterative method.

The analytical method requires information on several key points of the I-V characteristic curve, i.e. the current and voltage at the maximum power point (MPP), short-circuit current (ISC), open-circuit voltage (VOC), and slopes of the I-V characteristic curve at the axis of intersection. Ishaque *et al.,* (2012) used analytical method to extract PV parameters. However, analytical approach relies on the correctness of the selected points on the I-V characteristic curve (Ishaque *et al.,* 2012). Also, although it performs efficiently at STC for some models but it is unsuitable for varying weather conditions (Chenni *et al.,* 2007).

Evolutionary method appears to be a natural choice to extract the module parameters at conditions other than STC and it does not depends on the gradient and initial condition information (Ishaque, 2011; Ishaque *et al.,* 2011). Evolutionary method which includes global optimization techniques, genetic algorithm method, mimetic algorithm method, particle swarm optimization method and penalty-based differential evolution method have been used (Ishaque, 2012). Moldovan *et al.,* 2009 and Zagrouba *et al.,* 2010 used the genetic algorithm. Genetic Algorithm are generally slow and degrades for highly interactive fitness function (Zwe-Lee, 2004).

AIterative methods are the best options for parameter extraction. Different iterative methods have been used in literature but Newton-Raphson method (NRM) is observed to be the best-root-finding methods but its accuracy and convergence depends on the choice of initial condition (Pradhan, 2014). Five independent equations are necessary for extraction of the five unknown parameters such as I_{ph}, I_o, R_s, R_p and a for a single diode five-parameter model.
Jacobian matrix is required in the NRM method, the Jacobian matrix consists of twenty-five numbers of double derivative terms $\frac{\partial^2 f(x)}{\partial X}$ in addition to same number of single derivative terms $\frac{\partial f(x)}{\partial X}$ where X=[I_{ph} ,I_o, a, R_s, R_p] and f(x) is any five unique functions dependent on X. Due to this fact, NRM is very complex, lengthy and error-prone. Also, singularity problem which is division by zero may arise if initial parameters are not properly chosen (Pradhan, 2014). Unknown parameters are calculated by varying each of these parameters in five dependent loops until the maximum power of PV module matches with the power at maximum power point.

The Newton Raphson Method (NRM)

The Newton Raphson method is an iterative method that consists in estimates of a given function f(x) with an initial guess (Reis, 2017).
The method is obtained through the Taylor series expansion in (x-xo) given in equation (5)

$$f(x) = f(x_0) + f'(x_0)(x-x_0) + \frac{1}{2!}f''(x_0)(x-x_0)^2 + \ldots + \frac{1}{n!}f^n(x_0)(x-x_0)^n \qquad \ldots\ldots\ldots(5)$$

Assume the initial guess is close to the real root of the equation, then (x-x_o) is small enough and only the first terms are important for estimating the value of the root x_n. Therefore given x_n, the point x_{n+1} will be obtained by intersecting the tangent line at f(x) in xn with the x-axis as shown in equation (6). Mathematically

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \qquad \ldots\ldots\ldots\ldots(6)$$

MATERIALS AND METHODS

Materials used include the specification sheet of ROY solar module, computer system and MATLAB R2010a. The objective functions were derived and equations for Jacobian matrix were also derived. These equations were subsequently programmed for simulation.

Mathematical Derivations

The seven parameters, Photocurrent Iph, Reverse saturation currents I_{o1} and I_{o2}, ideality factors a_1 and a_2, Series resistance R_s and Parrallel resistance R_p which are the real required PV parameters. The objective functions needed to estimate these parameters were derived at open-circuit, short-circuit and maximum power conditions as follows.

Applying these conditions (open-circuit, short-circuit and maximum power condition) to equation (4) yields $f_1(x)$ to $f_3(x)$.

$$f_1(x) = 0 = I_{ph} - I_{o1}\left(\exp\left(\frac{V_{oc}}{a_1 V_t}\right) - 1\right) - I_{o2}\left(\exp\left(\frac{V_{oc}}{a_2 V_t}\right) - 1\right) - \frac{V_{oc}}{R_p} \qquad \ldots\ldots\ldots(7)$$

At short circuit condition (I=I_{sc}; V=0)

$$f_2(x) = 0 = I_{ph} - I_o\left(\exp\left(\frac{I_{sc}R_s}{a_1 V_t}\right) - 1\right) - I \qquad \ldots\ldots\ldots(8)$$

At maximum power condition (I=Imp; V=Vmp)

$$f_3(x) = 0 = I_{ph} - I_{o1}\left(\exp\left(\frac{V_{mp} + I_{mp}R_s}{a_1 V_t}\right) - 1\right) - I_{o2}\left(\exp\left(\frac{V_{mp} + I_{mp}R_s}{a_2 V_t}\right) - 1\right) - \frac{V_{mp} + I_{mp}R_s}{R_p} - I_{mp} \qquad \ldots\ldots\ldots(9)$$

$$\frac{dI}{dV}\left(1 + \frac{I_{o1}R_s}{a_1 V_t}\exp\left(\frac{V - IR_s}{a_1 V_t}\right) + \frac{I_{o2}R_s}{a_2 V_t}\exp\left(\frac{V - IR_s}{a_2 V_t}\right) + \frac{R_s}{R_p}\right) = -\left[\frac{I_{o1}}{a_1 V_t}\exp\left(\frac{V + IR_s}{a_1 V_t}\right) + \frac{I_{o2}}{a_2 V_t}\exp\left(\frac{V - IR_s}{a_2 V_t}\right) + \frac{1}{R_p}\right] \qquad \ldots\ldots\ldots\ldots\ldots(10)$$

Again at open circuit condition (I=0; V=V_{oc})

$$\frac{dI}{dV} = -\frac{1}{R_s} \qquad \ldots\ldots\ldots(11)$$

$$f_4(x) = 0 = \frac{\frac{I_{o1}}{a_1 V_t}\exp\left(\frac{V - IR_s}{a_1 V_t}\right) - \frac{I_{o2}}{a_2 V_t}\exp\left(\frac{V + IR_s}{a_2 V_t}\right) + \frac{1}{R_p}}{1 + \frac{I_{o1}R_s}{a_1 V_t}\exp\left(\frac{V + IR_s}{a_1 V_t}\right) + \frac{I_{o2}R_s}{a_2 V_t}\exp\left(\frac{V + IR_s}{a_2 V_t}\right) + \frac{R_s}{R_p}} - \frac{1}{R_s} \qquad \ldots\ldots(12)$$

Again at short circuit condition (I=Isc; V=0)

$$\frac{dI}{dV} = -\frac{1}{R_p} \qquad \ldots\ldots\ldots(13)$$

$$f_5(x) = 0 = \frac{\frac{I_{o1}}{a_1 V_t}\exp\left(\frac{I_{sc}R_s}{a_1 V_t}\right) + \frac{I_{o2}}{a_2 V_t}\exp\left(\frac{I_{sc}R_s}{a_2 V_t}\right) + \frac{1}{R_p}}{1 + \frac{I_{o1}R_s}{a_1 V_t}\exp\left(\frac{I_{sc}R_s}{a_1 V_t}\right) + \frac{I_{o2}R_s}{a_2 V_t}\exp\left(\frac{I_{sc}R_s}{a_2 V_t}\right) + \frac{R_s}{R_p}} - \frac{1}{R_p} \qquad \ldots\ldots(14)$$

Again at maximum power point (I=Imp; V = Vmp)

$$\frac{dI}{dV} = -\frac{I_{mp}}{V_{mp}} \qquad \ldots\ldots\ldots(15)$$

$$f_6(x) = 0 = V_{mp}\left[\frac{\frac{I_{o1}}{a_1 V_t}\exp\left(\frac{V_{mp} + I_{mp}R_s}{a_1 V_t}\right) + \frac{I_{o2}}{a_2 V_t}\exp\left(\frac{V_{mp} + I_{mp}R_s}{a_2 V_t}\right) + \frac{1}{R_p}}{1 + \frac{I_{o1}R_s}{a_1 V_t}\exp\left(\frac{V_{mp} + I_{mp}R_s}{a_1 V_t}\right) + \frac{I_{o2}R_s}{a_2 V_t}\exp\left(\frac{V_{mp} + I_{mp}R_s}{a_2 V_t}\right) + \frac{R_s}{R_p}}\right] - I_{mp} \qquad \ldots\ldots(16)$$

The last function was derived from the assumption that the sum of the two-diode ideality factors should be at least 2.2 (Villalva *et al.,* 2009).

$$f_7(x) = 0 = a_1 + a_2 - 2.2 \quad \text{.................(17)}$$

2.2 Estimation of the Seven-Parameter

Newton-Raphson method was established using previously derived seven equations in the form f(x)=0. X is an array of the seven-parameter as shown in equation. The Jacobian matrix J(x) was derived from the seven-equation using in-built differentiation function in MATLAB.

$$F(x) = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \\ f_6 \\ f_7 \end{bmatrix} \quad \text{..................(18)}$$

$$J(x) = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_1}{\partial x_7} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_2}{\partial x_7} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_3}{\partial x_7} \\ \frac{\partial f_4}{\partial x_1} & \frac{\partial f_4}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_4}{\partial x_7} \\ \frac{\partial f_5}{\partial x_1} & \frac{\partial f_5}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_5}{\partial x_7} \\ \frac{\partial f_6}{\partial x_1} & \frac{\partial f_6}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_6}{\partial x_7} \\ \frac{\partial f_7}{\partial x_1} & \frac{\partial f_7}{\partial x_2} & \cdots\cdots\cdots & \frac{\partial f_7}{\partial x_7} \end{bmatrix} \quad \text{............(19)}$$

$$X_{n+1} = X_n - J^{-1}(X) \bullet F(X_n) \quad \text{................................(20)}$$

2.3 Initialization of Variables

The photocurrent is a function of temperature and solar irradiance and is expressed as

$$I_{pv} = (I_{scn} + K_i * (T - T_n)) * \frac{G}{G_n} \quad \text{.............(21)}$$

The two diodes reverse saturation currents are

$$I_{01} = \frac{(I_{scn} + K_i * (T - T_n))}{\exp\left(\frac{V_{ocn} + K_v * (T - T_n)}{a_1 * V_t}\right) - 1} \quad \text{.....................(22)}$$

$$I_{02} = \frac{(I_{scn} + K_i * (T - T_n))}{\exp\left(\frac{V_{ocn} + K_v * (T - T_n)}{a_2 * V_t}\right) - 1} \quad \text{.....................(23)}$$

$a_1=1$ ....(24)

$a_2=1.2$ ....(25)

$$R_p = \frac{V_{mp}}{I_{sc} - I_{mp}} - \frac{V_{oc} - V_{mp}}{I_{mp}} \quad \text{...................(26)}$$

Rs=0 ....(27)

The equations were coded in MATLAB environment and simulated using the values of the parameter on the nameplate of Roy PV module and some constants as shown in Table 1.

Table 1: Parameters used in the simulation

S/N	Symbol	Quantity	Value
1	Ns	No of Series cell	36
2	T	Temperature at STC	25+273= 298K
3	K	Boltsman constant	$1.3806e^{-23}$
4	q	Charge of electron	$1.602e^{-23}$
5	V_{mp}	Output voltage at maximum power	16.579V
6	I_{mp}	Output current at maximum power	7.458mA
7	V_{oc}	Open circuit voltage	20.681V
8	I_{sc}	Short Circuit Current	7.78mA

Fig. 5 and Fig. 6 show implementation flowchart used in matlab and the source code to compute the jacobian matrices respectively. The code was written in the script file of matlab. Constants and necessary data from the pv module data sheet were entered into the code.

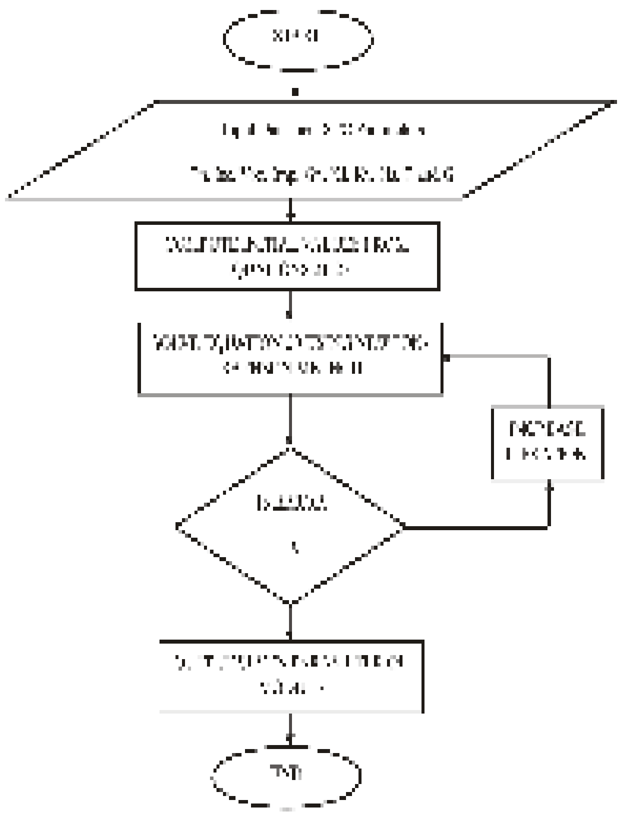

Fig. 5: Implementation Flowchart Used In Matlab

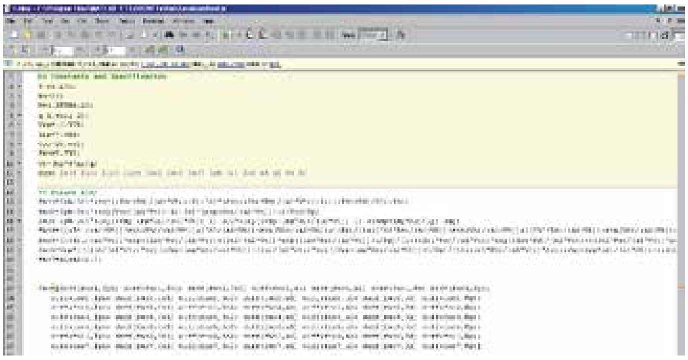

Fig. 6: The Source Code To Compute The Jacobian Matrix

RESULTS AND DISCUSSION

The snapshot of the objective functions f_1-f_7 was taken as shown in fig. 7. These functions are needed in computing the Jacobian matrix which will eventually be used in computing the parameters using newton raphson iterative method. For example, the objective functions f_1 and f_7 are indicated as equations 29-30.

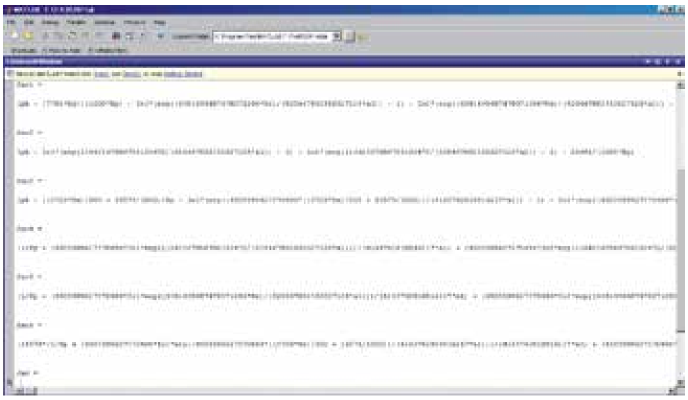

Fig. 7: The Calculated Functions for the Jacobian Matrix In Matlab

$$Fnc1 = Iph - \frac{7703 * Rs}{1000 * Rp} - Io1 * \left(exp\left(\frac{43014394074780071296 * Rs}{520467852352027125 * a1}\right) - 1\right) - Io2 * \left(exp\left(\frac{43014394074780071296 * Rs}{520467852352027125 * a2}\right) - 1\right) - \frac{7703}{1000} \quad ......(29)$$

$$fnc7 = a1 + a2 - 11/5 \quad ....(30)$$

Fig.s 8-14 are the snapshots of each of the column of the Jacobian matrix obtained in MATLAB using equation (18-20).

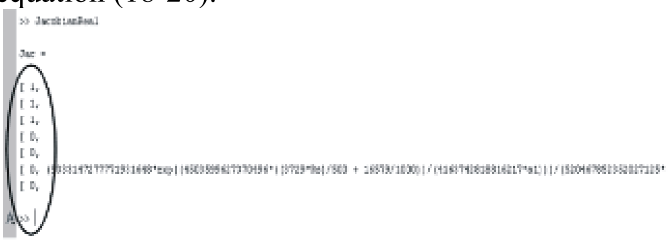

Fig. 8: Snapshot of the first column of the Jacobian Matrix

Fig. 9: Snapshot of the second column of the Jacobian Matrix

Fig. 10: Snapshot of the third column of the Jacobian Matrix

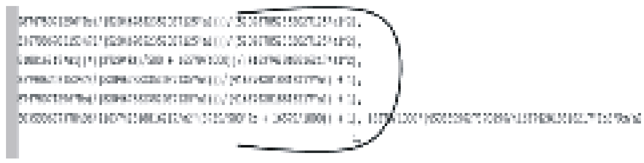

Fig. 11: Snapshot of the fourth column of the Jacobian Matrix

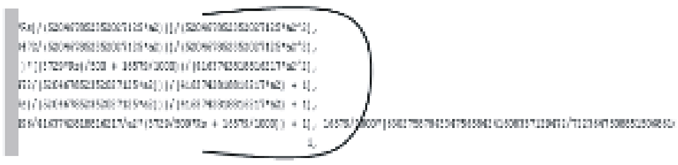

Fig. 12: Snapshot of the fifth column of the Jacobian Matrix

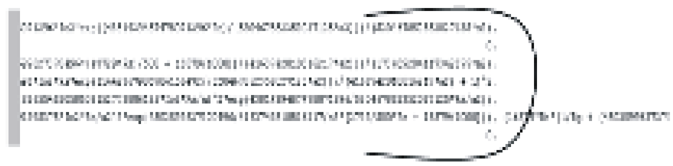

Fig. 13: Snapshot of the sixth column of the Jacobian Matrix

Fig. 14: Snapshot of the seventh column of the Jacobian Matrix

This Jacobian matrix which is a 7x7 matrix will be used in computing Photocurrent Iph, Reverse saturation currents I_{o1} and I_{o2}, ideality factors a1 and a_2, Series resistance Rs and Parallel resistance Rp which are the real required parameters. It means that for any type of PV module, one can use this code to determine the Jacobian matrix which can be used to understand all their necessary parameters under any new conditions of irradiance and temperature and then, obtain the I-V and P-V characteristics.

CONCLUSION

The presented results of this studywork show a detailed modeling and estimation of the PV module parameters of a double diode model. It was implemented under MATLAB/Editor. This model was obtained in accordance with the fundamentals of semiconductors and the PV cell technology. The codes developed for this model can be used to determine the Jacobian matrix for estimating PV parameters under various conditions to obtain the I-V and P-V characteristics. This model will be considered as a tool which can be used to study all types of PV modules available in markets, especially, their behavior under different weather data of standard test conditions (STC).

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