PHOTOVOLTAIC CELL MODELLING AND SIMULATION STRATEGIES

Pervez Hameed Shaikh*, Anwar Ali Sahito*, and Aslam Pervaiz Memon**

ABSTRACT

The main focus of this paper is on the modeling of photovoltaic panels or modules that are composed of numerous basic cells. The constituent which impact on the precision of PV simulation is the equivalent circuit modeling primarily encompasses the estimation of the non-linear I-V and P-V characteristics. The assessment, analysis and depiction of PV model will ultimately describe the parameters for the development of maximum power point tracking (MPPT) algorithm along with power conditioners compatibility. This paper intends to collectively organize and assess the mathematical model of the PV cells and to drive the best possible modeling for the continuous varying solar radiation and even under partial shade conditions.

Keywords-Photovoltaic, non-linear, model, solar, simulation

Nomenclature defined in equations as follows:

- e : Charge of electron (1.602×10^{-19} C).
- k : Boltzmann's constant (1.38×10^{-23} J/K).
- I0 : Reverse saturation current for diode.
- Iph : Photo-current, a function of junction temperature and irradiation level (5 A).
- Ic : Output current of cell, A.
- Rs : Series resistance of cell.
- Tc : Operating temp. of reference cell (20 °C).
- Vc : Output voltage of cell, V.
- Ipv,n: Light-generated current in Amperes at the nominal condition (usually 25 °C and 1000W/m^2),
- ΔT = T – Tn (being T and Tn the actual and nominal temperatures in Kelvin)
- G : Irradiation on the device surfacein [W/m^2],
- Gn : Nominal irradiation in [W/m^2].
- Eg : Energy band-gap of the semiconductor at normal ambient temperatures.
- I_0,n : Nominal saturation current
- Ns : Cells connected in Series.
- Np : Cells connected in Parallel.
- Vt,n : Thermal voltage of Ns (series-connected cells) at the nominal temperature Tn.

1. INTRODUCTION

Solar photovoltaic is a single stage non-conventional energy transformation source which makes electrical energy from light energy. Edmund Becquerel explained in 1839, as the action of falling of light quantum on silver glazed platinum electrode. PV cell is assemble by thin wafers of p-type and n-type material to form a junction. In dark, it has output characteristics similar to a simple diode [1]. The major benefits that PV generators possess, which has resulted in its huge utilization since last two decades, are small lead duration for designing and fixing new systems, matching of output power with peak load burdens, immobile structure, environmental friendly, portable, light weight, high efficiency per unit of weight, noise free, high useful operating life and no moving parts [2].

When PV cell is exposed to light (e.g. sunlight), photons with superior energy band gap of the semiconductor are enthralled thus creating an electron-hole pair. The inner electric fields of pn-junction will cause to be swept across and will produce current proportional to the incident irradiation.

The current flows in the external circuit when PV cell is shorted and shunted internally through intrinsic p-n junction when open circuited. Thus, setup the open circuit voltage exponential characteristics of the cell analogous to that of a diode [3]. PV cells are replicated as a bi-terminal device, which conducts as of a diode in dark and also produce electrical energy when exposed to sunlight.

The constituent which impact on the precision of PV simulation is the equivalent circuit modeling primarily

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encompasses the estimation of the non-linear I-V and P-V characteristics. The assessment, analysis and depiction of PV model will ultimately describe the algorithm parameters for the development of maximum power point tracking (MPPT) algorithm along with power conditioners [4-5].

2. PHOTOVOLTAIC PARAMATRIC EQUIVALENCE

Fig. 1 shows the modest form of equivalent circuit of a solar cell comprises of current source and one or two shunt diodes [5-9]. Current voltage (I-V) characteristivs of cell are determined by the diode [1]. The output of current source is directly proportional to the incident light falling on the cell.

The equivalent circuit models are an appropriate and common approach to pronounce the electrical activities of system devices. In general, an equivalent circuit deals three core benefits:

- Easy to implement with complex electrical systems;
- Permits the system properties depiction in a homogenous and curtailed way in a simple analytical model
- Deliver insights into the multifarious physical progressions which occur within the device/system.

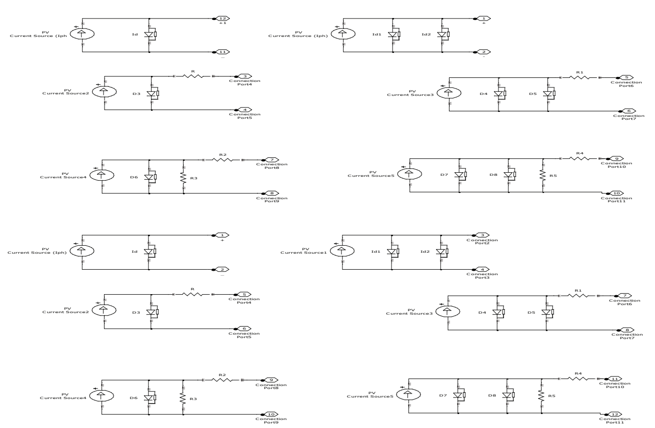

Fig. 1: Ideal Equivalent Circuit Models

a. Ideal Photovoltaic Cell

Electrically, the photovoltaic cell is analogous to a current source in parallel with a non-linear, asymmetric resistive component, i.e., a diode (Fig. 1). Once the cell is brightened, the ideal cell generates photocurrent proportionate to the light concentration. The photocurrent is in quotient amongst the adjustable resistance of non-linear diode and the connected burden, in a ratio which hang on the resistance of connected load and radiance level. It only necessitates three parameters, explicitly; the open circuit voltage (V_{OC}), the short-circuit current (I_{SC}) and the diode ideality factor (A) [10].

b. Realist Photovoltaic Cell Parameters

In a real photovoltaic cell the power extracted from the PV cell depends on several factors which were neglected in the ideal state as defined under:

(i) Parasitic Resistances

In genuine PV cells, the power is dissipated in the resistance of the connections, finite conductivity of neutral regions and also the leakage currents within the sides. These possessions depict electrical equivalence to two parasitic resistances in series R_S (causes the opposition to flow of electrons and holes), its value is so small to withdraw from the circuit [5, 15, 17-19]. Shunt resistance R_{sh} (depicts recombination of electron hole pairs inside the pn junction). Shunt resistance is usually very high and is being neglected for simplification [11-13, 14-18].

(ii) Diode Ideality Factors

The electron hole pair alignment at the junction express the ideality factor of diode meant with 'A'. Its value is generally presumed to be 1 by several authors, referring to P-N junction formation and diffusion of charge carriers across the barrier [20]. In case of two diodes, the second diode is set equal to 2, in accord with the traps notion of recombination [21]. The ideality factor is typically constant at minute currents and ample variation is observed at high currents. This may also vary with temperature [19, 22].

(iii) Thermal Voltage

The diode thermal voltage due to the units of voltage, represented as

$$V_T = k_B \frac{T}{q_e} \qquad (1)$$

where junction temperature (T) is assumed to be controlledor prior known extent, kB is Boltzmann's c onstant, and qe is the elementary electronic charge. Its value is typically around 26 mV at ambient temperature [23].

3. SINGLE DIODE MODEL

Alternatively termed one-diode or single exponential model is the modest and utmost used model for representation of PV cells. Nevertheless unpractical, the simplest PV cell equivalence is single diode model, a current source in parallel to a diode [4, 9, 15, 18, and 19]. This model is enhanced with the insertion of one series resistance, RS [1, 12, 23-26]. In spite of its simplicity to practical approach, the proposed model unveils severe scarcities, with leakage currents within PV cells due to impurities near the junction and inhomogeneous crystal lattice and also when endangered to temperature deviations. The value of RS is quite small and this parameter is often ignored [22, 26 and 28].

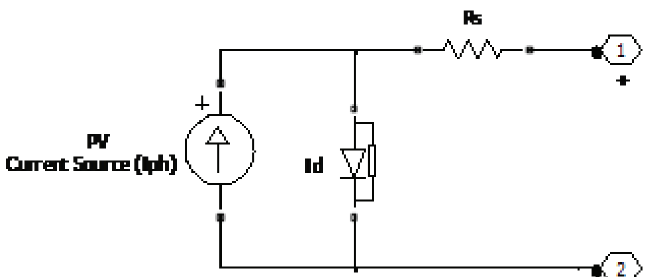

Fig. 2: One diode 3 parametric model

$$I_{pv} = I_{ph} - I_d \left(exp \left(q \, \frac{V_{pv} + IR_s}{Akt} \right) \right) \quad (2)$$

A supplementary shunt resistance R_p included in it for leakage currents, non-uniform crystal fabrication structure causes model extension which burdens substantial computational effort, though improvement is achieved in its output power characteristics [20, 21, 29-31]. The value of R_p is generally neglected in [17-19] to simplify the model.

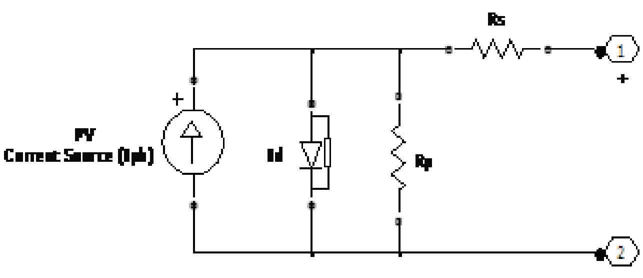

Fig. 3: One diode 4 parametric model

$$I_{pv} = I_{ph} - I_d \left(exp \left(q \, \frac{V_{pv} + IR_s}{Akt} \right) \right) \frac{V_{pv} + IR_s}{R_p} \quad (3)$$

This KVL model devises the graphical current-voltage and power-voltage characteristics as shown in Fig. 4, where the three notable points are highlighted i-e open circuited voltage (V_{OC}, 0), short circuited current (0, I_{SC}) and the maximum power point (V_{mp}, I_{mp}). These models are supposed to immune from recombination loss in the depletion region but atlow voltage level, the recombination implies a significant power loss in PV cells. This does not satisfactorily express in the single exponential model. Thus an addition of another shunt diode will comprehensively show this recombination loss.

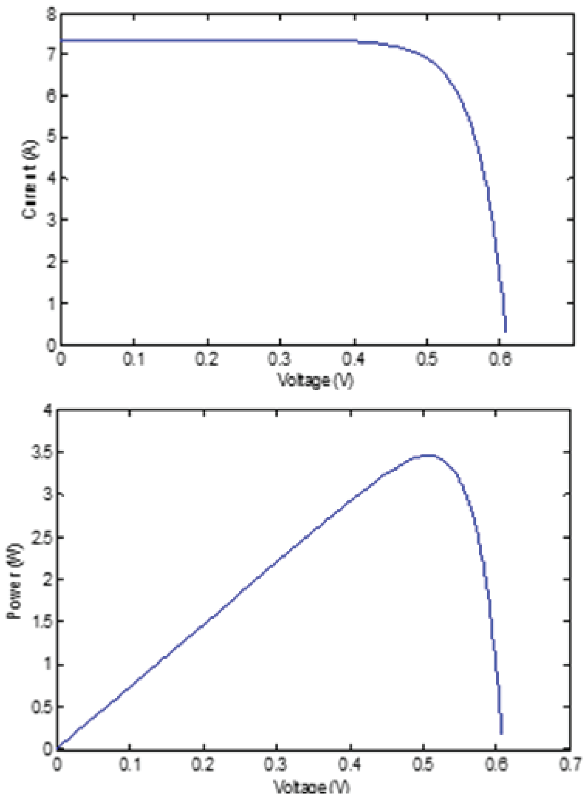

Fig. 4: PV cell characteristics; I-V and P-V (MATLAB ®)

4. TWO-DIODE-MODEL FOR PV CELLS

An even more exact modeling could be achieved by the double-diode or double exponential model with like or unlike diode ideality factors, are joined in parallel. This recombination loss concern in depletion region at low voltage level leads to a more precise model with the addition of another shunt diode for the depiction of the substantial loss [31]. Consideration of this loss leads to a more precise model known as the two-diode model [32]. This model has the benefit of improved precision but has the hindrance of dependency on increased number of parameters. The major impact of the proposed model is temperature variation sensitivity increases as the saturation current is doubled.

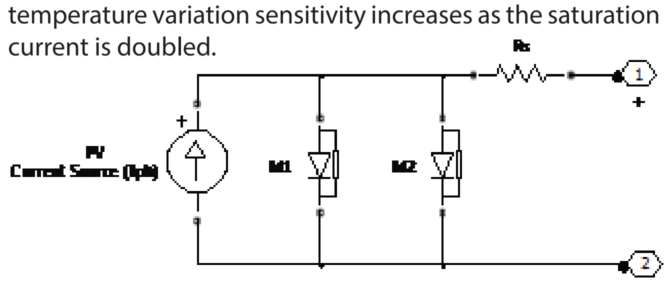

Fig. 5: Double diode 4 parametric model

$$I_{pv} = I_{ph} - I_{d_1} \left(ecp \left(q \, \frac{V_{pv} + IR_s}{Akt} \right) \right) - I_{d_2} \left(ecp \left(q \, \frac{V_{pv} + IR_s}{Akt} \right) \right) \quad (4)$$

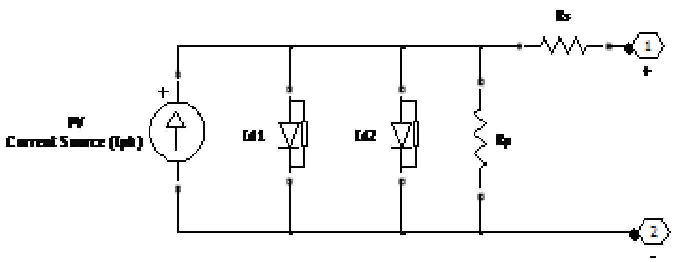

Fig. 6: Double diode 5 parametric model

$$I_{pv} = I_{ph} - Id_1 \left(ecp \left(q \frac{V_{pv} + IR_S}{Akt} \right) \right) - Id_2 \left(ecp \left(q \frac{V_{pv} + IR_S}{Akt} \right) \right) - \left(\frac{V_{pv} + IR_S}{R_p} \right) \quad (5)$$

- Introducing following points to the model will enhance accuracy, complexity and sophistication [4]:

- Temperature dependence of the diode saturation current I0 and the photocurrent I_L.

- A better and accurate shape between the open-circuited voltage and peak power point by a series resistance R_S which represents the internal current flow loss.

- Shunt resistance (R_{Sh}), in parallel with the diode relates to the leakage current to ground probably possess high value or being usually neglected

- Bringing two diodes in parallel with an independent set of saturation currents or letting the Q-F (quality factor) of the diode to have variable parameter insteading of making it fixed at 1 or 2.

- A fair and a common assumption for an ideal cell is $R_S = R_{Sh} = 0$, [6]. A modest complexity model is used to reach at realistic approach.

The rational simulation time management along with the values of approximation of all of the model parameters is the core challenge. Numerous computational techniques have been already offered [17]-[20] and in all these, additional fresh coefficients are presented, ultimately causes computational effort to increase. In determining initial values of parameters, some empirical solutions are pursued. Whereas, scrutinizing its physical features such as the electron coefficient diffusion, lifespan of marginal carriers, intrinsic carrier concentration and other semiconductor parameters [21]-[24] describing the physical conduct of a cell. Since the data about semiconductor is not always accessible in PV datasheets commercially.

Different simulation software are available in market for analyzing mathematical models of the PV cell, Some of the commonly used software are PVsyst, PVcad, SolarPro, PV-DesignPro and PV-Spice. These software packages are costly and rarely have provision of power converters to be interfaced with PV arrays [25].

5. DIODE MODEL JUSTIFICATION

Numerous model variants are established in collected works Watson (1960) [1, 4] offered a two-diode model with identical exponents for crystalline-Si PV cell. Wolf and Rauschenbach (1963) [4] focused the effects of dispersed series resistance PV cells, and resulting the analogous mathematical model [4], but they overlooked the loss caused by shunt current due to the high shunt resistance (RP=13.8 kΩ) consideration in their tentative 2-cm2 mono-crystalline Si cell. Müllejans et al. (2004) [5] used 5-parameter model, supposing prior diode ideality factors n1=1 and n2=2. They stated shunt resistance RP values of practical (large-area) poly-Si cells is as low as 6.6 Ω. In [6, 8, and 13] have also implemented the similar 5-parameter version with the consideration of recombination diode insignificant. Coors and Böhm (1997) [7] have initiated IEC-891 superior 7-parameter variant and Blaesser's technique in I-V curves improvement [7].
Ouennoughi and Chegaar (1999) [13] single-diode estimate have been used and applied the classical equation to a PV module, providing option for number of series cells portraying their ideality factor. This approach thus creates the assessment of p-n junction parameters for cells and modules less straight-forward. Lo Brano et al. (2010) [14] ideality factor of diode using dimensions Volts/Kelvin integrating the fundamental charge and Boltzmann's constant. Thus, stripping qe and k_B, classical (dimensionless) ideality factors of 0.87 and 0.73 achieved, which are not physical. The 3D effects in PV cell are investigated at [4] and also evaluating current flow configuration in distributed series resistance thus becomes too modest and precise model the output from a PV cell. Since, at-least an extra diode and an additional resistor be added for understanding localized loss mechanisms, includes partial resistance enriched recombination [15], for the PV modules tested here, we assume that none of their cells requires such complicated modeling when illuminated outdoors.

6. PARAMETER EXTRACTION APPROACH

(i) Non-linear Fitting

The shunt resistance of a PV cell can be found near short circuit with linear fitting. Since this method each time may not for modules, as bypass diodes get activated at decreased voltage levels. The approximate equivalence of photo-current and short circuit current is assumed for only crystalline cells and the saturation currents in that are smaller in magnitude of several order and also the series resistance is much smaller than the shunt one. Non-linear fitting is preferred for estimation of parameters [39, 43-48] most of them assume the fixed values of ideality diode factor 1 and 2, while selecting other parameters with fixtures. This technique requires the initial values for non-linear fitting approaches resulting satisfactory curve fits. The non-linear curve fittings are complicated in modeling and even in computer coding. Care must be taken for representative values, with less complexity observations. [47, 50 and 51]

(ii) Semi-log Partial Linear Fitting

To analyze data of p-n junction [45, 52-54] and to discriminate linear part of semi-logarithmic plot, this dominates the two exponential terms. The linear region slope is q_e/nkVT (q_e/NSnkVT for modules) is used to extract diode ideality and current intercept for linear fit provides reverse saturation current. In [45, 53] diode ideality is temperature dependent and series resistance compensation effects the linear deviations at increased voltages. Since physically consistent parameters may not be extracted from tangents to semi logarithmic curve, as there might be conduction and recombination prevailing [55]. The series-resistance effect (R_S is normally not known prior) hence, compensated and the unfavorable effects acquire place at modest voltages, thus interfering with R_S. These all detrimental mechanisms (shunting, recombination or resistive losses) lead to slight rise in the local ideality factor at enhanced voltage level.

(iii) Multiple Quad Dark Analyses

The above two methodologies reviewed may also be pertinent to dark characteristics of PV cells, used in arrangement with irradiated cells to explore certain parameters. An intrinsic difficulty of this technique is imprecise result for R_S caused by altered current drift patterns (e.g. current crowding) in brightened versus dark cells [56, 43]. Reverse current vs. voltage features are also used to find individual parameters.
Dark and multiple-quadrant methods are out of scope yet; we have focused on illuminated forward bias and partial shade data.

7. CONCLUSION

The exploration of PV solar cell has been augmented in last decade to confront the world energy need and improved cell/module performance features at cheaper rates. A PV cell is presumed as a large area forward bias diode p-n junction with a photo voltage, thus created from electron disorder with incident photons at junction. Most of the factors which affect the output of PV cell must be taken into consideration along with the quality issues as ripple generation and the dynamic modeling of PV cell. Since, not only the output of solar cell is reduced but also the I-V chararcteristics of PV array or module are affected by the constant partial shading. The problem is further aggravated by the reverse-biasing of the shaded cells, making it a diode with high resistance, that gets over-heated when the illumination difference is fairly large. Thus, there is need for the development of appropriate model that offer benign, amiable and a comprehensive photovoltaic solar system operating under continuous partial shading conditions and changing sun position for static or BIPV systems.

ACKNOWLEDGMENT

This research work is dedicated to our professors of department of Electrical engineering Mehran university of engineering and technology Jamshoro. They helped us in carrying out this research work.

REFERENCES

[1] Walker G "Evaluating MPPT converter topologies using a matlab PV model," J. Elect. Electron. Eng., Vol. 21, No. 1, pp. 45–55, 2001.

[2] Carlson D. E "Recent Advances in Photovoltaics", Proceedings of the Intersociety Engineering Conference on Energy Conversion, pp. 621-626, 1995.

[3] Petreuş D, Fărcaş C and Ciocan I "Modeling and Simulation of Photovoltaic Cells" Electronics and Telecommunication, Vol. 49, No. 1, 2008.

[4] Ishaque K, Salam Z. and Taheri H "Accurate MATLAB Simulink PV System Simulator Based on a Two-Diode Model" Journal of Power Electronics, Vol. 11, No. 2, March 2011.

[5] Benavides N.D and Chapman P.L "Modeling the Effect of Voltage Ripple on the Power Output of Photovoltaic Modules," IEEE Trans. Ind. Electron., Vol. 55, No. 7, pp. 2638–2643, Jul. 2008.

[6] Tan Y.T, Kirschen D.S and Jenkins N "A model of PV generation suitable for stability analysis," IEEE Trans. Energy Convers., Vol. 19, No. 4, pp. 748–755, 2004.

[7] Kajihara A and Harakawa A.T "Model of photovoltaic cell circuits under partial shading," in Proc. ICIT, pp. 866–870, 2005.

[8] Ishaque K, Salam Z and Syafaruddin "A Comprehensive MATLAB Simulink PV system simulator with Partial Shading Capability based on Two Diode Model", Solar Energy, Vol. 85, pp. 2217–2227, 2011.

[9] Patel H. and Agarwal V. “MATLAB-based modeling to study the effects of partial shading on PV array char-acteristics”. IEEE Transactions on Energy Conversion, Vol. 23, No. 1, pp. 302-310, 2008.

[10] Kuo Y.C. Liang T.J and Chen J.H “Novel maximum-power-point-tracking controller for photovoltaic energy conversion system”. IEEE Trans-actions on Industrial Electronics, Vol. 48, No. 3, pp. 594–601, June 2001.

[11] Xiao W, Dunford W.G and Capel A. “A novel modeling method for photovoltaic cells”. In Proc. IEEE 35th Annual Power Electronics Specialists Conference, PESC, Vol. 3, pp. 1950–1956, 2004.

[12] Yusof Y, Sayuti S.H, Latif M.A and Wanik M.Z.C. “Modeling and simulation of maximum power point tracker for photovoltaic system”. In Proc. National Power and Energy Conference, PECon, pp. 88–93, 2004.

[13] Khouzam K., Ly C.K and Ng P.Y “Simulation and real-time modelling of space pho-tovoltaic systems”. In IEEE 1st World Conference on Photovoltaic Energy Conversion, Conference Record of the 24th IEEE Photovoltaic Specialists Conference, Vol. 2, pp. 2038–2041, 1994.

[14] Glass M.C “Improved solar array power point model with SPICE realization” In Proc. 31st Intersociety Energy Conversion Engineering Conference, IECEC, Vol. 1, pp. 286–291, August 1996.

[15] Altas I.H. and Sharaf A.M. “A photovoltaic array simulation model for MATLAB Simulink GUI environment”, In Proc. International Conference on Clean Electrical Power, ICCEP, p. 341–345, 2007.

[16] Matagne E, Chenni R. and El Bachtiri R. “A photo-voltaic cell model based on nominal data only”, In roc. International Conference on Power Engineering, Energy and Electrical Drives, Powereng, pp. 562–565, 2007.

[17] Tan Y.T, Kirschen D.S. and Jenkins N. “A model of PV generation suitable for stability analysis” IEEE Transactions on Energy Conversion, Vol. 19, No. 4, pp. 748–755, 2004.

[18] Kajihara A. and Harakawa A.T “Model of Photovoltaic Cell Circuits under Partial Shading”, In Proc. IEEE Inter-national Conference on Industrial Technology, ICIT, pp. 866–870, 2005.

[19] Carrero C, Amador J. and Arnaltes S. “A single procedure for helping PV designers to select silicon PV module and evaluate the loss resistances,” Renewable Energy, Vol. 32, No. 15, pp. 2579–2589, Dec. 2007.

[20] Liu S. and Dougal R.A. “Dynamic multiphysics model for solar array,” IEEE Trans. Energy Convers., Vol. 17, No. 2, pp. 285–294, Jun. 2002.

[21] Celik A.N and Acikgoz N. “Modelling and experimental verification of the operating current of mono-crystalline photovoltaic modules using four and five parameter models”, Applied Energy, Vol. 84, No. 1, pp. 1–15, 2007.

[22] Gonz´alez-Longatt F. “Model of photovoltaic module in MATLAB”, 2do Congreso Beroamericano De Estudiantes De Ingeniería Eléctrica, Electrónica Y Computación, Ii Cibelec, 2005.

[23] Kuo Y.C, Liang T.J and Chen J.F “Novel maximum-power-point tracking controller for photovoltaic energy conversion system,” IEEE Trans. Ind. Electron., Vol. 48, No. 3, pp. 594–601, Jun. 2001.

[24] Yusof Y, Sayuti S.H, Latif M.A and Wanik M.Z.C “Modeling and simulation of maximum power point tracker for photovoltaic system,” in Proc. PEC, pp. 88–93, 2004.

[25] Vitorino M.A, Hartmann L.V, Lima A.M.N and Correa M.B.R “Using the model of the solar cell for determining the maximum power point of photovoltaic systems”, In Proc. European Conference on Power Elec-tronics and Applications, pp. 1–10, 2007.

[26] Sera D, Teodorescu R and Rodriguez P. “PV panel model based on datasheet values”, In Proc. IEEE Inter-national Symposium on Industrial Electronics, ISIE, pp. 2392–2396, 2007.

[27] Yadir S, Benhmida M. Sidki M. Assaid E. and Khaidar M. “New method for extracting the model physical parameters of solar cell using explicit analytic solutions of current-voltage equation,” in Proc. ICM, pp. 390–393, 2009.

[28] Aazou S. and Assaid E.M “Modeling real photovoltaic solar cell using Maple,” in Proc. ICM, pp. 394–397, 2009.

[29] Villalva M.G, Gazoli J.R and Filho E.R "Comprehensive approach to modeling and simulation of photovoltaic arrays," IEEE Trans. Power Electron., Vol. 24, No. 5, pp. 1198–1208, May 2009.

[30] Dondi D, Brunelli D, Benini L, Pavan P, Bertac-chini A. and Larcher L "Photovoltaic cell modeling for solar energy powered sensor networks", In Proc. 2nd International Workshop on Advances in Sensors and Interface, IWASI, pp. 1–6, 2007.

[31] Yi-Bo W. Chun-Sheng W, Hua L. and Hong-Hua X "Steady-state model and power flow analysis of grid-connected photovoltaic power system", In Proc. IEEE International Conference on Industrial Technology, ICIT, pp. 1–6, 2008.

[32] Veerachary M "PSIM circuit-oriented simulator model for the nonlinear photovoltaic sources", IEEE Transactions on Aerospace and Electronic Systems, Vol. 42, No. 2, pp. 735– 740, April 2006.

[33] Gow A. and Manning C.D "Development of a photovoltaic array model for use in power-electronics simulation studies," IEE Proc. Elect. Power Appl., Vol. 146, No. 2, pp. 193–200, 1999.

[34] Nishioka K, Sakitani N. Kurobe K, Yamamoto Y, Ishikawa Y. Uraoka Y and Fuyuki T "Analysis of the temperature characteristics in polycrystalline si solar cells using modified equivalent circuit model," Jpn. J. Appl. Phys., Vol, 42, pp. 7175-7179, Dec. 2003.

[35] Hovinen A "Fitting of the Solar Cell I/V-curve to the Two Diode Model," Physica Scripta, Vol. 54, pp. 175-176, Jun. 1994.

[36] Gow J.A and Manning C.D "Development of a model for photovoltaic arrays suitable for use in simulation studies of solar energy conversion systems," in Proc. 6th Int. Conf. Power Electron. Variable Speed Drives, pp. 69–74, 1996.

[37] Hyvarinen J. and Karila J. "New analysis method for crystalline siliconcells," in Proc. WCPEC, Vol. 2, pp. 1521–1524, 2003.

[38] Chowdhury S, Taylor G.A, Chowdhury S.P, Saha A.K and Song Y.H "Modelling, simulation and performance analysis of a PV array in an embedded environment," in Proc. UPEC, pp. 781–785, 2007.

[39] Nishioka K, Sakitani N, Uraoka Y and Fuyuki T "Analysis of multi-crystalline silicon solar cells by modified 3-diode equivalent circuit model taking leakage current through periphery into consideration," Solar Energy Mater. Solar Cells, Vol. 91, No. 13, pp. 1222–1227, 2007.

[40] Houssamo I, Sechilariu M, Locment F. and Friedrich G "Identification of Photovoltaic Array Model Parameters. Modeling and Experimental Verification", International Conference on Renewable Energies and Power Quality (ICREPQ'10) Granada (Spain), 23th to 25th March, 2010

[41] Yordanov G.H, Midtgård O.M and Saetre T.O "Extracting parameters from semi-log plots of polycrystalline Silicon PV modules I-V data: Double-exponential model revisited", presented at the 35th IEEE Photovoltaic Specialists Conference (2010).

[42] Appelbaum J, Chait A. and Thompson D "Parameter estimation and screening of solar cells", Progress in Photovoltaics: Research and Applications Vol. 1, 1993.

[43] Gottschalg R. Rommel M. Infield D.G and Kearney M.J "Comparison of different methods for the parameter determination of the solar cell double exponential equation", Proceedings 14th European Photovoltaic Solar Energy Conference, Vol. 1, pp. 321, 1997.

[44] Wolf M and Rauschenbach H "Series resistance effects on solar cell measurements", Advanced Energy Conversion, Vol. 3, pp. 455, 1963.

[45] Müllejans H, Hyvärinen J, Karila J, Dunlop E.D "Reliability of the routine 2-diode model fitting of PV modules", Proceedings 19th European Photovoltaic Solar Energy Conference pp. 2459, 2004.

[46] Coors S. and Böhm M. "Validation and comparison of curve correction procedures for silicon solar cells", Proceedings 14th European Photovoltaic Solar Energy Conference, Vol. 1, pp. 220, 1997.

[47] Charles J.P, Bordure G, Khoury A and Mialhe P "Consistency of the double exponential model with the physical mechanisms of conduction for a solar cell under illumination", Journal of Physics D: Applied Physics, Vol. 18, pp. 2261, 1985.

[48] Araújo G.L, Cuevas A. and Ruiz J.M "The effect of distributed series resistance on the dark and illuminated current-voltage characteristics of solar cells", IEEE Transactions on Electron Devices, Vol. 33,

pp. 391, 1986.

[49] Carstensen J. Abdollahinia A. A. Schütt, H. Föll, "Characterization of the grid design by fitting of the distributed serial grid resistance to CELLO resistance maps and global I-V curves", Proceedings 24th European Photovoltaic Solar Energy Conference, pp. 516, 2009.

[50] Ouennoughi Z, and Chegaar M "A simpler method for extracting solar cell parameters using the conductance method", Solid State Electronics, Vol. 43, pp. 1985, 1999.

[51] Streetman B.G and Banerjee S. "Solid State Electronic Devices", 5th Edition, Prentice Hall, Chapter 5.6.3 "Ohmic Losses", pp. 217, 2000.

[52] Sze S.M and Ng K.K "Physics of Semiconductor Devices", 3rd Edition, John Wiley & Sons, Chapter 2 "p-n Junctions", pp. 79, 2007.

[53] McIntosh K.R "Lumps, humps and bumps: Three detrimental effects in the current-voltage curve of silicon solar cells", PhD Thesis, University of New South Wales (2001).

[54] Pysch D, Mette A. and S.W. Glunz, "A review and comparison of different methods to determine the series resistance of solar cells", Solar Energy Materials & Solar Cells, Vol. 91, pp.1698, 2007.

[55] Breitenstein O, Bauer J, Lotnyk A, and Wagner J.M "Defect induced non-ideal dark I-V characteristics of solar cells", Superlattices and Microstrutures, Elsevier, Vol. 45, pp. 182-189, 2009.

[56] Ramabadran R, and Mathur B "Effect of shading on series and parallel connected solar PV modules", Modern Applied Science, Vol. 3, No. 10, pp. 32- 42, 2009.