International Journal of Applied Engineering Research ISSN 0973-4562 Volume 10, Number 14 (2015) pp 34244-34250

Modeling Of Solar Panel As Gendralised Structure

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ABSTRACT
Day-by-day the energy demand is increasing and thus the need for a renewable source that will not harm the environment are of major importance. Some projections state that by 2050 the energy requirement will triple. Yet majority of the energy requirements is satisfied by fossil fuels but by the use of photovoltaic systems could help in supplying the power demands. In this paper we have dealt with problem that persists with the modeling of photovoltaic device. The disputed point where various models of photovoltaic device face is the number of unknown parameters which are not mentioned in the datasheet. Various methodologies have been proposed in order to determine these unknown parameters. Basically, in this work, two of the proposed methods are being studied and then related. This can give a brief idea to the manufacturers who design power electronics products about the easy-to-use modeling methods that can be used in simulation of photovoltaic arrays.

I INTRODUCTION

Photovoltaic's (PVs) are arrays (combination of cells) that contain a solar voltaic material that converts solar power into electrical power. PV cell is a basic device for Photovoltaic Systems, Such systems include multiple devices like mechanical and electrical connections and mountings and various means of regulating and modifying the electrical output. substances that are used for photovoltaic are mono-crystalline silica, polycrystalline silica, microcrystalline silica, cadmium telluride and copper indium selenide. The current(I) and voltage(V) available at the PV device terminals can be directly used for small loads like lighting systems or small DC motors. In order to extract maximum amount of power from PV array can be model converters so that it can track Maximum Power Point (MPP).

In a photovoltaic (PV) solar system, the power generating devices are the PV modules, often called PV panels. For a large-scale PV system, a number of PV panels are connected in series to form a 'string'. These strings are then connected in parallel to form an 'array'. The PV modules, or panels, are comprised of a number of PV cells also connected in series and shunt configuration. These PV cells produce DC current and DC junction voltage on the incidence of light because of PV effect on semiconductors. As a result of the series and shunt combination of the cells in a module, the PV module can be equivalently characterised by an increased level of current and voltage. The current against voltage $(I - V)$ characteristic of a PV cell, and thereby a PV panel, is not linear [1–5] and highly dependent on solar irradiation As a result, for a particular amount of solar irradiation, there is a peak point of power corresponding to the voltage at which the PV panel can supply maximum of power for that irradiance level [1–5]. Moreover, these characteristics are temperature dependent. Therefore the dynamic model of the PV solar panels represented by a conventional linear DC voltage or current source is not appropriate.

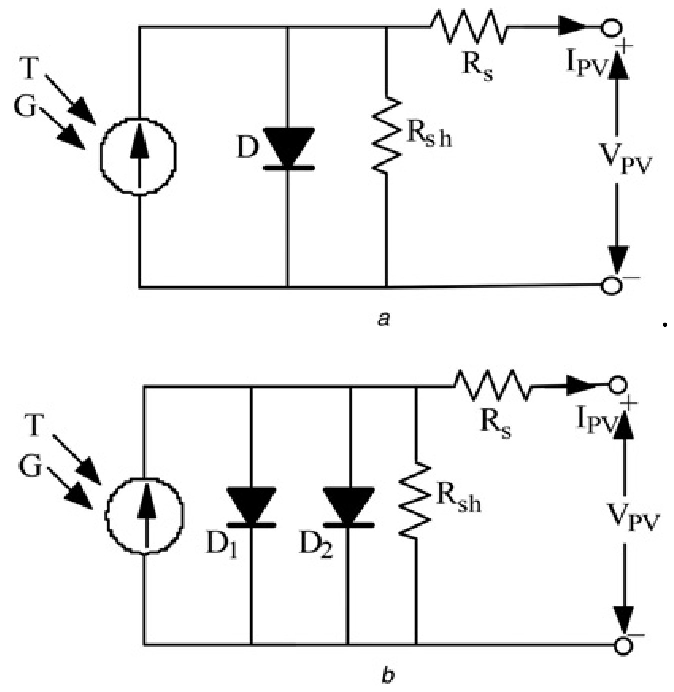

Fig. 1 Equivalent circuit of PV a Single diode model b Double diode model

At the circuit level, the PV solar cells are represented by either an equivalent single diode circuit [6] as shown in Fig. 1a or a two diode circuit [7] as illustrated in Fig. 1b. In this

figure, G denotes the solar irradiation, Temp is the temperature, Rs is the equivalent series resistance of the cell and Rsh is the equivalent shunt resistance of the cell. The single diode model offers simplicity and accuracy and, istherefore, widely used [6, 8, 9]. The modelling of solar panels using different commercially available softwares, such as MATLAB/SIMULINK, SPICE, SABER etc., is reported in [7–20]. For modelling PV panels,
these software applications utilise lookup tables for the equivalent source current output according to the I − V curves [8], approximate diode current equations embedded in an equivalent current source [9], equivalent linear DC voltage source [10], programme coding for current output corresponding to an equivalent source terminal voltage [11], I − V characteristic curve of the PV cell for the determination of equivalent source parameters [7] and material specific standard energy band gap data [17] which are not provided by manufacturer datasheets. Implementation of the diode equations requires an important parameter known as ‘diode ideality factor’, n, that needs to be determined. In most cases, this parameter is approximated or taken from the properties of cell manufacturing materials.

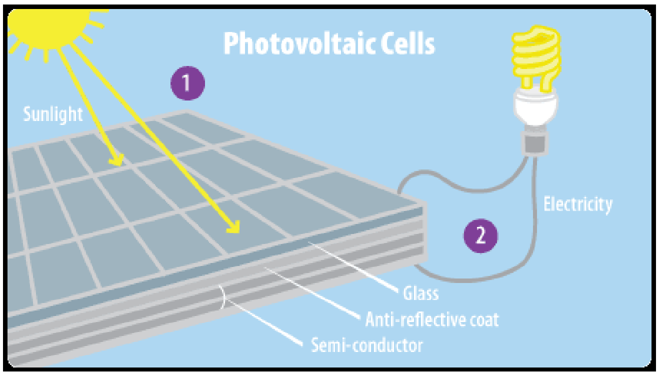

Fig 2 photo voltaic cell model 1.Sunlight hits the surface of the photovoltaic cell. 2.A material called semi-conductor converts the light into electricity.

Although the aforementioned papers utilise standard diode equations to model PV cells, it is important to precisely determine the equivalent series resistance Rs and the shunt resistance Rsh because of the non-linearity of the equations [21]. Some papers have used I − V characteristic curves to determine the equivalent Rs of the PV cell by either neglecting Rsh of the PV cell [11, 12] or considering the value of Rsh to be quite high and the effect of Rs to be more dominant than Rsh in certain operating regions. Both the resistances have also been determined through iterative techniques [13–16] or with the locus of diode ideality factor in conjunction with the I − V curve [18], or through a curve fitting technique [19]. A double exponential equation based model of a PV cell is proposed in [20]. Several models have also been developed in EMTDC/PSCAD software while performing fault analysis [22], analysing the achievement of maximum power point tracking (MPPT) [23] and developing PV array models [24, 25]. These models are developed using approximate equations by neglecting both Rs and Rsh [22]. Some models typically use a number of pre-defined constants with FORTRAN coding [23]. One of them [24] utilises pre-defined constants derived from I − V curves. A circuit-based piecewise linearisation technique through trial and error has been used to develop the model of PV source [25].
Section II relates the mathematical modelling of PV panels. Section III presents various simulation results and validation of the predicted output of the developed model with different manufacturer’s datasheet values. Section IV presents the model validation with calculated data. Section V concludes the paper.

II MATHEMATICAL FORMULATION AND PV PANEL MODEL

A standard PV panel datasheet provides the following parameters: open circuit voltage, Voc, short-circuit current Isc, Isc, maximum power point (MPP) voltage, Vm, MPP current, Im and maximum power, PM, at standard test condition (STC) which is defined as the solar irradiation of 1000 W/m2 equivalent to one sun at 25°C. In addition to these parameters, the temperature coefficients at Voc and Is care provided by these datasheets. Some datasheets also provide the corresponding currents, voltages and power at some other non-STC temperature and irradiation which is defined as nominal operating cell temperature (NOCT)[1–5]. However, the equivalent representation of a single diode circuit as shown in Fig. 1a also requires values of resistances Rs and Rsh, which are not provided by the standard manufacturer’s datasheet. Hence, the primary objective of this section is to determine a general expression for the parameters Rs and Rsh and develop the PV panel model, accordingly II Mathematical formulation and PV panel This paper follows [12–18, 28–30] in which the shunt resistance of each cell is modelled in the equivalent model of the PV module, and especially reference [18] which considers the cells to be identical. In actual practice, all the cells in a module may not be identical and the value of shunt resistance of each cell may differ because ofmanufacturing defects, aging, cracking etc. Still, this mismatch between the cells is quite small, as a large mismatch can potentially cause circulating currents in non-identical cells and create hot spot heating [21]. The values of Rsh and Rs of cells derived in this paper indeed correspond to the average values of these resistances, and may be deemed to incorporate the effect of slight mismatch among different cells

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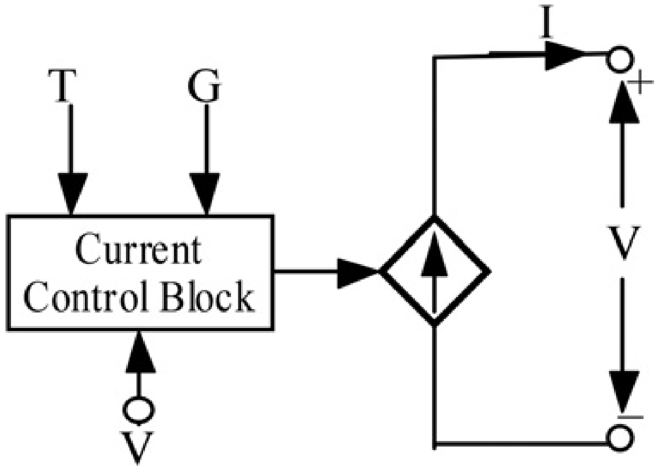

Fig. 3 model of single diode circuit of PV panel

In this modelling, a non-iterative technique is developed to obtain both Rs and Rsh by using the standard datasheet values given at STC and thereby ensuring simplicity and accuracy. In addition, by using the manufacturer datasheet values, a simple systematic procedure is presented to predetermine the diode ideality factor, n, which greatly influences the values of Rs and Rsh and, thereby, the output of the PV panel. Usually, a PV panel is constituted of a series–parallel combination of PV solar cells. The number of solar cells in series determines the net increased voltage across the terminal of PV panel and the No of solar cell in parallel determines the net increased output current of the PV panel. Therefore the equivalent single diode circuit of Fig. 1a can be represented as an equivalent single PV cell unit as shown in Fig. 2a, where V is the PV panel voltage, VPV is the PV cell voltage, I is the PV panel current, IPV is the PV cell current, ns is the number of series connected PV cells in a PV panel and np is the number of parallel connected PV cells in a PV panel. To develop the PV panel model, the series–parallel combination of the equivalent single diode circuit of PV cell is transformed into a single controlled current source [9] as illustrated in Fig. 2b. In this figure, a 'current control block' controls the output current of the controlled current source, equivalently, the output current I of PV panel according to its terminal voltage V, solar irradiation G and cell operating temperature T. The 'current control block' embeds a set of equations. The set of equations are described below

The PV panel voltage and current output in Fig. 2b can be expressed as V = VPV × ns and I = IPV × np, respectively.The contact between voltage and current with respect to different solar irradiations and temperatures for a standard PV cell can be expressed by a set of basic diode equation [14]

$$\frac{I}{n_p} = I_{ph} - I_0 \left[e^{((q*((v/(n_s))) + (I/n_p)) R_s))/nKT)} - 1 \right] - \frac{n_p V + n_s I R_s}{n_p n_s R_{sh}} \tag{1}$$

The photo current, Iph, is a direct function of solar radiation, G, and is expressed as [14]

$$I_{ph} = I_{ph(STC)} \frac{G}{G_{nom}} \tag{2}$$

where Iph(STC) is the photo current at standard solar irradiation level, Gnom.The reverse aturation current I0 is a function of temperature and is usually expressed with the equation containing the energy band gap function, Vg [6, 11, 23]

$$I_O = I_{o(STC)} \left(\frac{T_s}{T_2}\right)^3 e^{((qV_s[1+K_v(T_s-T_2)])} / (nKT_sT_2) \tag{3}$$

where Ts is the temperature at STC, T2 is another operating temperature and Kv is the temperature coefficient at open circuit voltage expressed in %/°C. The energy band gap is yet another unknown parameter and depends on the manufacturing material and process. Therefore an alternate technique is followed to determine I0 by using the STC condition: T = Ts, G = Gnom, I0 = I0(STC) and Iph = Iph(STC). Applying two conditions at STC in (1), that is, (i) short-circuit condition V = 0 and current I = Isc(STC) and (ii) open circuit condition where I = 0 and V = Voc(STC), we obtain expressions (4) and (5). It is noted, the quantities, Iph(STC) and Io(STC) denote PV cell level currents whereas Isc(STC) denotes PV module level current

$$\frac{I_{sc(STC)}}{n_p} = I_{ph(STC)} - I_{0(STC)} \left[e^{\left(\frac{q[I_{sc(STC)} R_s]}{nKT_s n_p}\right)} - 1 \right] - \frac{I_{sc(STC)} R_s}{n_p R_{sh}} \tag{4}$$

The short-circuit current Isc and open circuit voltage Voc canbe expressed in terms of temperature coefficient to relate them with the quantities at STC as follows [14]

$$I_{sc} = I_{sc(STC)}[1 + K_i(T - T_s)] \tag{5}$$

$$V_{0c} = V_{oc(STC)}[1 + K_v(T - T_s)] \tag{6}$$

Here, Ki is the temperature coefficient of PV short-circuitcurrent and Kv is the temperature coefficient of PV open circuit voltage at STC. Both are expressed in %/°C. Ts is the standard temperature at STC, nom is the solar radiation at STC.

Determination of shunt resistance (Rsh) and series resistance (Rs):

the resistances Rs and Rsh are not strictly constant with respect to temperature However, this dependence of Rs and Rsh on temperature is rather small and has been reported to cause a maximum error in peak power of only 1.19% and < 0.04% around NOCT [8]. For this reason, the temperature dependence of Rs and Rsh has been ignored in this paper. To determine these parameters from (11) at STC, it is assumed that

$$e^{((qI_{sc(STC)}\{1+K_v(T-T_s)\}R_s)/(nKTn_p))}=1 \quad (7)$$

This basis of this assumption is given below.The exponential term of (12) is directly proportional to Rs and Isc and inversely proportional to n. The worst-case (high) value of this exponent is now evaluated. The maximum temperature T is considered to be Ts ± 50°C, where Ts = 25°C. Considering the diode to be ideal gives the lowest value of n = 1 The approximate value of Rs is determined to be the slope of the I − V characteristic curve at Voc and is expressed as Rs = np(Voc − Vm)/nsIm [21]. For typical parameters at STC [1], the approximate maximum value of Rs is found to be 0.181 Ω. Therefore, for the worst-case scenario, the left side is calculated to be 1.09, which is very close to 1.0 and thus justifying the assumption.
Ageing tends to increase the value of Rs [and decrease the value of Isc and form factor,thereby increasing the value of diode ideality factor. Variations in these parameters, although small tend to make the exponential term smaller, and the overall value of expression closer to unity. Hence, the modelling assumption is valid even for conditions caused by ageing.
Therefore, the term can be approximated as unity. At STC, replacing T by Ts and G by Gnom, and using the above approximation, can be approximated as follows Therefore the expression for shunt resistance can be derived by using the fact that at MPP the derivative of power with respect to voltage is zero.

$$R_{sh}=\frac{[n_sI_{sc(STC)}R_s-n_pV_{oc(STC)}]\left[e^{((q(n_pV_m+n_sI_mR_s))/(nKT_sn_sn_p))}\right]q+nKT_sn_sn_p[e^{((qV_{oc(STC)})/(nKT_sn_s))}-1]}{((n_sI_mnKT_sn_p\{e^{\left(\frac{qV_{oc(STC)}}{nKT_sn_s}\right)}-1\}])/((n_pV_m-n_sI_mR_s)))-[e^{\left(\frac{q(n_pV_m+n_sI_mR_s)}{nKT_sn_sn_p}\right)}]qn_sI_{sc(STC)}} \quad (8)$$

$$R_s=\frac{nKT_sn_p}{qI_m}\ln\left[e^{\left(\frac{qV_{oc(STC)}}{nKT_sn_s}\right)}-\frac{I_m}{I_{sc(STC)}}\left\{e^{((qV_{oc(STC)})/nKT_sn_s))}-1\right\}\right]-\frac{n_pV_m}{n_sI_m} \quad (9)$$

Determination of diode ideality factor n:
it is noted from output current expression, shunt resistance Rsh expression and series resistance Rs expression that all are dependent on the diode ideality factor n which differs based on cell type because of its manufacturing process.The MPP is dependent on the value of n

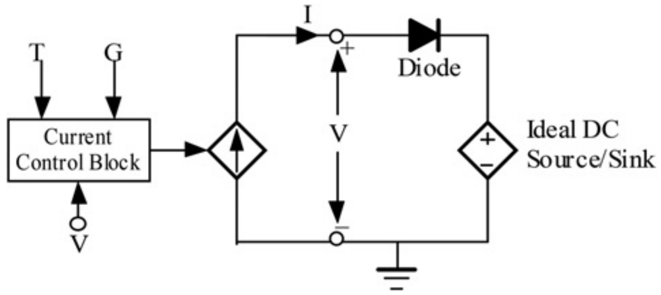

Fig. 4 DC circuit to determine diode ideality factor, n

4 MODEL VALIDATION WITH EXPERIMENTAL DATA
The datasheet parameter values may not differ from experimental values for a newly manufactured PV module as the solar module parameters are provided based on laboratory tests at the manufacturing facility. However, these experimental values may become slightly different from the datasheet values because of ageing etc. A model validation study is now presented in Table 2. The DC power output predicted from the proposed model is validated against measured power output data for a polycrystalline module provided by National Institute of Standards and Technology (NIST)
In Table 2, it is seen from row (1) that the predicted valueof DC power at STC (1000 W/m2) is identical to the measured power output. When the temperature increases to 39.5°C for a small incidence angle θb of 27.8° as in row (2), the error between measured and predicted output is < 0.1%. Even when the temperature rises to 47°C as in row (3), the error is only about 4%. This error is attributed to an increased angle of incidence of solar radiation which is evident when comparing results of rows (2) and (4). The proposed model is thus validated with respect to temperature variation. Figure 5 shows the irration level vs photo current characterizes It is noted that the proposed model uses only the manufacturer's datasheet values which are given at zero incidence angle. If the experimental data at non-STC conditions are available at zero incidence angle, the predicted power output from the proposed model is expected to correlate even better with the measured results.

Table 1 Datasheet parameters at STC [1–5] and determined values of Rs, Rsh and n

Item description	FS-270	LDK-230P-20	LDK-235P-20
nominal power (±5%), PM, W	70	230	235
voltage at PMPP, Vm, V	65.5	29.3	29.5
current at PMPP, Im, A	1.07	7.85	7.96
open circuit voltage, Voc, V	88.0	36.9	37.3
short-circuit current, Isc, A	1.23	8.43	8.5
number of cells in a panel	116	60	60
temperature coefficient or current	0.04%^{O}C	0.06%^{O}C	0.06%^{O}C
temperature coefficient for voltage (all –ve)	0.25%^{O}C	0.33%^{O}C	0.33%^{O}C
diode ideality factor, n	3.106	1.213	1.13
cell series resistance, Rs, Ω	0.029953	0.00527	0.00560
cell shunt resistance, Rsh, Ω	2043.11	2364.42	2938.29

Table 2 Comparison of model output with experimental results from NIST

No.	Irradiation, W/m2	Temperature, °C	NIST value, W	Proposed model, W (at θb = 0°)	Error,%
1	1000 (at θb = 0°)	25	125.8	125.8	0
2	882.6 (at θb = 27.8°)	39.5	106.8	106.8	0.09
3	696 (at θb = 43.3°)	47	77.4	80.65	4.02
4	189.8 (at θb = 57.8°)	36.5	21.2	18.96	10

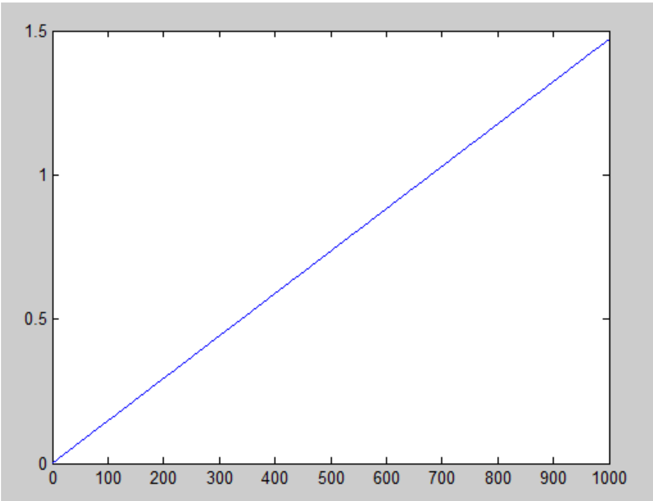

Fig 5 Solar irradiance vs. photo current

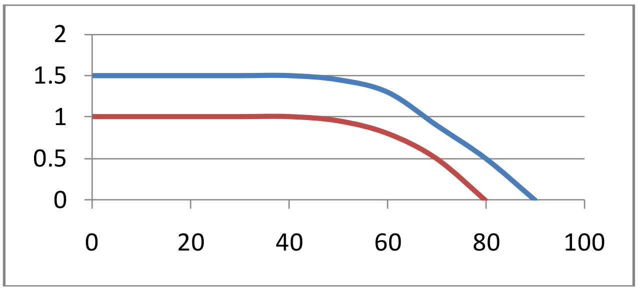

Fig 6 a I – V characteristic curves of FS 270

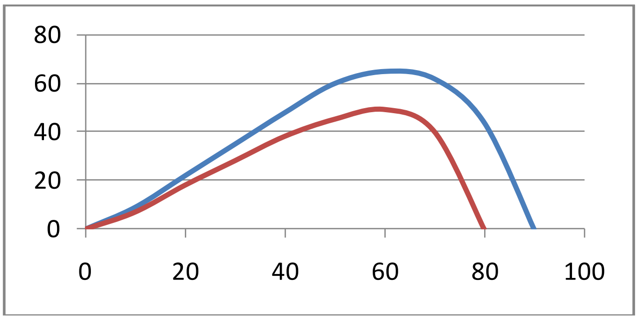

Fig 6 b P – V characteristic curves of FS 270

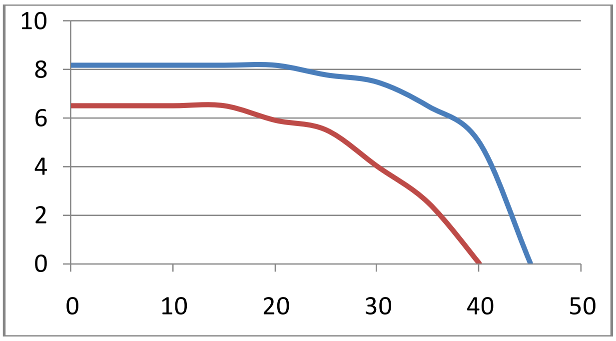

Fig 7 a I – V characteristic curves of LDK-230-20

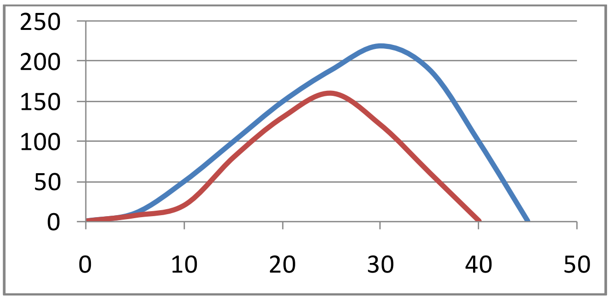

Fig 7 b P – V characteristic curves of LDK-230-20

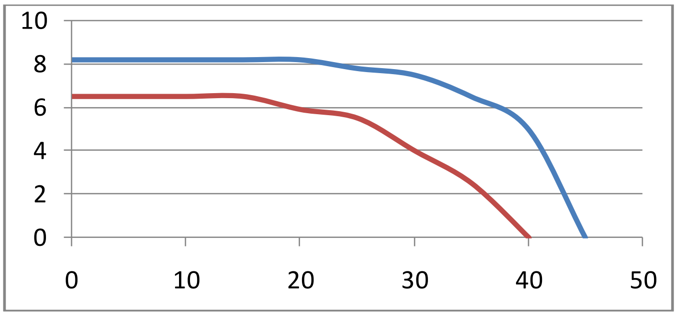

Fig 8 a I – V characteristic curves of LDK-235-20

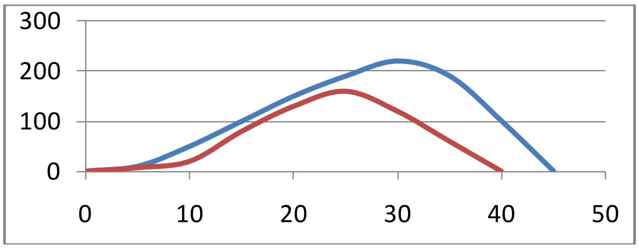

Fig 8 b P – V characteristic curves of LDK-235-20

5 CONCLUSIONS

In this paper, a generalised mathematical model of PV panel is presented. The PV panel is modelled by using only the parameters provided in standard manufacturers' datasheets. The proposed modelling technique determines all the PV panel or module parameters, that is, series resistance, shunt resistance and diode ideality factor at STCs without any explicit repetitive iteration method. This model is general and can be implemented in any software platform.However, in this paper, the proposed model is developed in the industry grade electromagnetic transient simulation software. This model is validated with three different commercially available PV panels using their datasheet values for parameters, such as, voltage, current and power at non-STC conditions. Moreover, the predicted output of the developed model correlates reasonably well with experimental results. Therefore this generalised model can be adopted for representing the performance of any PV panel at various operating conditions.

References

1 http://www.firstsolar.com/Downloads/pdf/Datasheet_s2_NA.pdf, accessed April 2011, FS series 2 PV Module Datasheet, Document ID:PD-5-401-02-NA June 2010

2 http://www.ldksolar.com accessed February 2013, Polycrystalline Modules LDK-230P-235P-20 Datasheet, V1 February 2012, LDKSolar Limited

3 http://www.ldksolar.com accessed February 2013, Monocrystalline Modules LDK-240D-245D-250D-20 Datasheet, V1 February 2012,LDK Solar Limited

4 http://www.us.sunpowercorp.com, http://www.solarplaza.com/top10- crystalline-module- efficiency/#sunpower, accessed September 2011, Sunpower E20/333 and E20/327 Solar Panels Datasheet, Document # 001-65483 Rev*B/A4_EN

5 http://www.sanyo-solar.eu/en, http://www.solarplaza.com/top10- crystalline-module- efficiency/#sunpower, accessed February 2013, Sanyo HIT Photovoltaic Module HIT-N240SE10, HIT-N235SE10, HIT-N230SE10 Datasheet

6 Liu, S., Dougal, R.A.: 'Dynamic multiphysics model for solar array',IEEE Trans. Energy Convers., 2002, 17, (2), pp. 285–294

7 Gow, J.A., Manning, C.D.: 'Development of a photovoltaic array model for use in power electronics simulation studies'. IEE Proc. Electric Power Applications, Loughborough University of Technology, March 1999, vol. 146, no 2, pp. 193–200

8 Xiao, W., Dunford, W.G., Capel, A.: 'A novel modeling method for photovoltaic cells'. Proc. 35th IEEE Power Electronics Specialist Conf., 2004, pp. 1950–1956

9 Jensen, M., Louie, R., Etezadi-Amoli, M., Fadali, M.S.: 'Model and simulation of a 75 kW PV solar array'. Proc. Transmission and Distribution Conf. Exposition, New Orleans, Louisiana, USA, 2010, pp. 1–5

10 Schonardie,M.F.,Martins,D.C.: 'Three-phase grid-connected photovoltaic system with active and reactive power control using dq0 transformation'. Proc. Power Electronics Specialists Conf., 2008, pp. 1202–1207

11 Walker, G.R.: 'Evaluating MPPT converter topologies using a MATLAB PV model', J. Electr. Electron. Eng., 2001, 21, (1), pp. 49–55

12 Gonzalez-Longatt, F.M.: 'Model of photovoltaic module in Matlab™',II CIBELEC, Puerto La Cruz, Venezuela, December 2005, pp. 1–5

13 Villalva, M.G., Gazoli, J.R., Filho, E.R.: 'Comprehensive approach to modeling and simulation of photovoltaic arrays', IEEE Trans. Power Electron., 2009, 24, (5), pp. 1198–1208

14 Sera, D., Teodorescu, R., Rodriguez, P.: 'PV panel model based on datasheet values'. Proc. IEEE Int. Symp. Industrial Electronics, 2007, pp. 2392–2396

15 Villalva, M.G., Gazoli, J.R., Filho, E.R.: 'Modeling and circuit-based simulation of photovoltaic arrays'. Proc. IEEE Brazilian Power Electronics Conf., 2009, pp. 1244–1254

16 Chang, C., Zhu, J., Tsai, H.: 'Model-based performance diagnosis for PV systems'. Proc. SICE Annual Conf., 2010, pp. 2139–2145

17 Attivissimo, F., Di, N., Savino, A., Spadavecchia, M.: 'Uncertainty analysis in photovoltaic cell parameter estimation', IEEE Trans. Instrum. Meas., 2012, 61, (5), pp. 1334–1342

18 Grandi, G., Sancineto, G.: 'Hardware modeling of photovoltaic panels'. Proc. ISES Solar World Congress, Göteborg, Sweden, 2003

19 Sandrolini, L., Artioli, M., Reggiani, U.: 'Numerical method for extraction of photovoltaic module double-diode model parameters through cluster analysis', Appl. Energy, 2010, 87, (2), pp. 442–451

20 Gottschalg, R., Rommel, M., Infield, D.G., et al.: ‘Comparison of different methods for the parameter determination of the solar cell double exponential equation’. Proc. 14th EUPVSEC, 1997, pp. 321–324

21 Gray, J.L.: ‘The physics of the solar cell’, in Luque, A., Hegedus, S. (Eds.): ‘Handbook of photovoltaic science and engineering’. (John Wiley & Sons, Inc., 2003), pp. 102–105

22 Wang, B., Huang, T., Jiang, B., Dong, X., Bo, Z.: ‘Dynamic modeling and transient fault analysis of feeder in distribution system with MWPV substation’. Proc. 45th Int. Universities Power Engineering Conf., 2010,pp. 1–5

23 Gupta, R., Gupta, G., Kastwar, D., Hussain, A., Ranjan, H.: ‘Modeling and design of MPPT controller for a PV module using PSCAD/EMTDC’. Proc. IEEE PES Innovative Smart Grid Technologies Conf.Europe, 2010, pp. 1–6

24 Xue, J., Yin, Z., Wu, B., Peng, J.: ‘Design of PV array model based on EMTDC/PSCAD’. Proc. IEEE Asia-Pacific Power and Energy Engineering Conf., 2009, pp. 1–5

25 Campbell, R.C.: ‘A circuit-based photovoltaic array model for power system studies’, Available at http://www.ee.washington.edu/research/sesame/publication/Conference/2007/Campbell_PWL_PV_Model _ NAPS2007.pdf, 17 July 2010