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Performance Evaluation of Solar Photovoltaic (PV) Array Based on Mathematical and Simulation Modelling: A Review

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ABSTRACT

Researchers have used different ways to simulate the output characteristics of solar cells, typically using the simulation tools such as LabVIEW, Pspice, PSIM and Matlab/Simulink. Over the last forty years several theoretical as well as experimental studies on the modelling of the solar photovoltaic system performance have been carried out. This article provides an exclusive survey on literatures close to the mathematical modelling and circuit based simulation for predicting the performance characteristics of solar photovoltaic panels. Research findings with valuable references have been provided in this study with the intention of furnishing the readers on the most typically used software tools, equivalent electric circuit, mathematical modelling and simulation of solar PV cells. In addition, results obtained from the previous studies were also presented and compared.

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INTRODUCTION

Modelling of photovoltaic cell is an essential topic of research since there is always a need to ensure that the generation of electricity via solar technologies prediction is as accurate as possible. In doing so, the concept of circuit equivalence to represent a solar cell has been widely established (Walker, 2001; Chenni *et al*., 2005). The current-voltage (I-V) characteristic of a PV cell characterizes the non-linear electrical behavior which strongly varies with sunlight intensity and the cell temperature. One-diode model and the two-diode model are the two most commonly used PV cell equivalent circuits (Lasnier and Ang, 1990). In this new era, there is a remarkable improvement in mathematical modelling and simulation of photovoltaic modules. This paper aims to provide the related review of literatures on the study performed by several researchers specifically in the mathematical modelling and simulation of solar photovoltaic cells to predict system performance.

Review on Simulation Modelling of PV Array:

Yang Gang and Chen Ming (2009) proposed a new type of LabVIEW method for the purpose of modelling and software design. Standard or general equivalent circuit model was utilized in this work. Influence of solar irradiation to the performance of solar cells was simulated and analyzed, and the I-V and P-V characteristics curves under different solar intensities were presented. The maximum power point tracking system was also analyzed by these authors where they found that the maximum power of solar cell increases significantly with the increase of solar radiation. Finally, the influence of internal or shunt resistance (R_{sh}) to the performance of solar cells was simulated using their system. Internal resistance is a key factor to the performance of solar cells as per the simulation results. It was found that the reduction of internal resistance will decrease the open circuit voltage and the fill factor, and also affects the photo electronic conversion efficiency (Table 1). Thus they concluded that for actual applications, the resistance should be built larger.

Table 1: Simulation results under different R_{sh} (Source: Yang Gang and Chen Ming).

R_{sh} (Ω)	U_{oc} (V)	P_m (W)	R’ (Ω)	FF
0.5	0.44883	0.50144	0.20234	0.44688
1	0.46739	0.63291	0.18448	0.46739
10	0.48122	0.76840	0.17325	0.63871
100	0.48249	0.78118	0.17006	0.64782
1000	0.48261	0.78422	0.16975	0.64998

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Modelling and simulation of grid connected solar photovoltaic system using Swing-Controlix software has been done by Tomas Skocil and Manuel Perez Donsion (2008). Simple model has been utilized in this paper as an equivalent circuit of a photovoltaic cell. Volt-ampere characteristic of a PV cell for a certain ambient irradiation and cell temperature only was illustrated. Then the effects of the ambient irradiation and cell temperature on the characteristics of the photovoltaic cell were analyzed by these authors. Fig. 1 shows the influence of solar irradiation on the current voltage characteristics of a PV cell. The change in ambient irradiation and cell temperature affects the current and voltage of a PV cell. In addition, the impact of series and parallel connection of two identical cells on the I-V curve was also shown. The dominant effect was concluded; with increasing cell's temperature causes linear decrease of the open circuit voltage, while open circuit voltage increases logarithmically with the ambient irradiation.

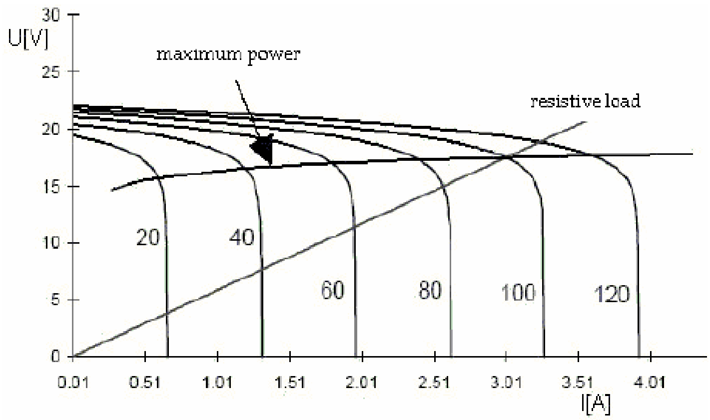

Fig. 1: Influence of radiation change on current and voltage of a PV cell (Courtesy: Tomas Skocil and Manuel Perez Donsion).

Marcelo Gradella Villalva *et al*. (2009) presented an easy yet accurate method of modelling photovoltaic arrays using Matlab Simulink (SymPower Systems BlockSet) and PSIM circuits to obtain the parameters of the array model using information from the datasheet. The photovoltaic panel mathematical model can be simulated with any circuit simulator. The detailed description of the equations of the model was presented and the model was also validated with experimental data. P-V model curves and experimental data of the Solarex MSX60 solar array at different temperatures and irradiation at 1000 W/m^2 is shown as an author's simulation example in Fig. 2. Wei Zhou *et al*. (2007) proposed a novel and simple model to predict the photovoltaic module performance for engineering applications. Five parameters (α, β, γ - Constant parameters, R_s – Series resistance, n_{MPP} – ideality factor at maximum power point) were introduced in this model. Under various solar irradiation intensities and module temperatures, the most important parameters which are the short circuit current, open circuit voltage, fill factor and maximum power output were determined. The developed model was validated by comparing with the field measured data from the existing building integrated photovoltaic (BIPV) system in Hong Kong polytechnic university campus. Their model verification was carried out for two states: sunny and cloudy conditions. They found good agreements between the simulated results and the field measured data. Comparison made between the measured and simulated power-output for a typical sunny summer-day by the authors is shown in Fig. 3.

Mrabti *et al*. (2010) worked on the simulation in Pspice and the experimentation operation of the photovoltaic panels and systems. Simple model was utilized as an equivalent circuit in this article. The optimal operation of PV panels as a function of the weather conditions such as solar irradiance, temperatures, etc., has been analyzed in detail. A photovoltaic system design with maximum power point tracker command to quickly confirm the optimum operation of photovoltaic panels was described. They obtained the results that the optimal electric properties (voltage, current and power) of PV panels depend on solar irradiation and the temperature. The typical characteristic of power-voltage is displayed in Fig. 4, which also represents the characteristics simulated in Pspice by the author. It has a good agreement between the laboratorial experimental measurement setup and simulation. Surya Kumari and Ch. Sai Babu (2012) developed and presented a mathematical model of PV cell using the Matlab-Simulink environment. Basic circuit equations of the solar cells have been utilized by these authors in order to develop the model. Parameters of the non-linear I-V equation have been determined in this paper by adjusting the curve at three points of open circuit, short circuit and maximum power. Best I-V equation for the single diode PV model has been found incorporating the effect of series and parallel resistances. Rustemli and Dincer (2011) presented and demonstrated the solar photovoltaic electrical model on Matlab/Simulink modeling and simulation platform. Simulation has been done using a typical Lorentz LA30-12S solar panel. I-V and P-V characteristics had been simulated and the results were shown in Matlab/Simulink graphics. Authors concluded that there is a reduction in the photovoltaic panel output power with the increment in the module temperature.

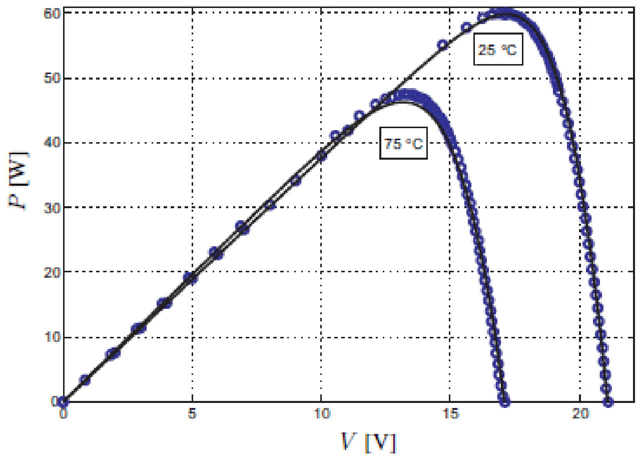

Fig. 2: Comparison chart (Courtesy: Marcelo Gradella Villalva *et al*).

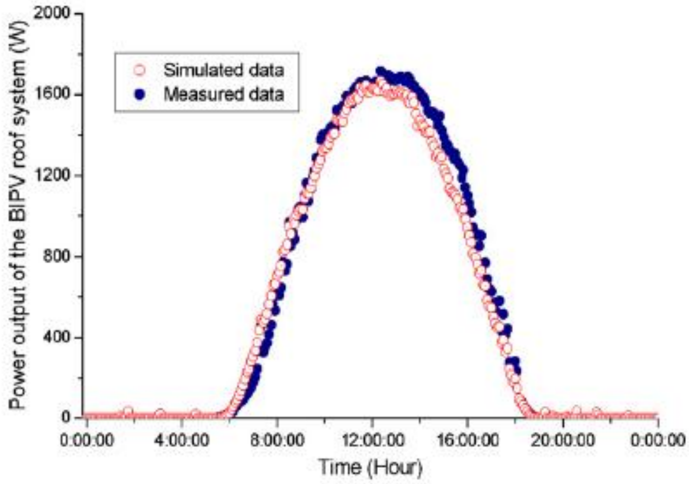

Fig. 3: P-V curve (Courtesy: Wei Zhou *et al*)

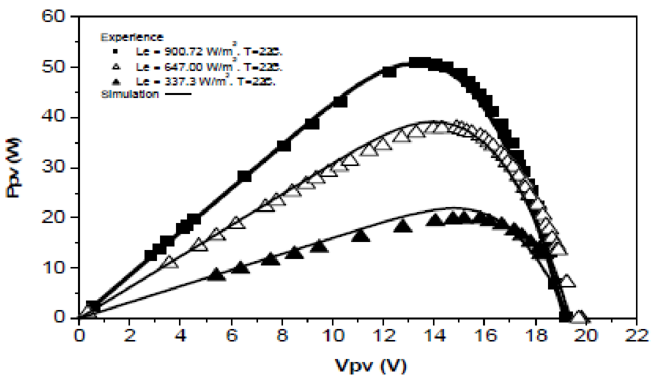

Fig. 4: Experimental P-V (■, Δ, ▲) and simulated in Pspice (——) curves. T: 22-25°C (Courtesy: Mrabti *et al*).

Development of a model which can simulate the performance of a photovoltaic (PV) system has been described by Andreea Maria Neaca and Mitica Iustinian Neaca (2009). This can simulate the performance of a photovoltaic (PV) system under specific meteorological conditions and transforming the DC current into AC current. Different methods such as Perturb and Observe (PAO), Incremental Conductance Technique (ICT), Constant Reference Voltage for testing the maximum power point trackers (MPPT) for different photovoltaic applications have been presented. They concluded that the ICT method has the highest efficiency in terms of extracting power from the PV array. Hamdaoui *et al*. (2009) proposed a method to monitor and control the performances of the PV systems. Their method comprised two parts in which the first one was to characterize the PV modules under various weather conditions. Attaining the power via simulation tool and comparing with those obtained in real time was the second part. Simulation model was developed using Matlab/Simulink software. They concluded that the second part of their method could not be validated in real time due to material problem, so that the simulation of the power produced by PV module was validated using the data accessed from Homer software. According to the result shown in Fig. 5, a good agreement was found between the results obtained using Homer software and those obtained by the developed simulation model.

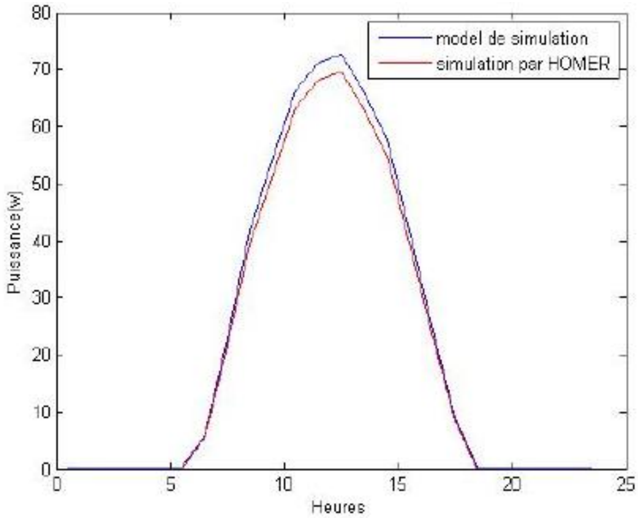

Fig. 5: Simulation of the power produced by the solar module (Courtesy: Hamdaoui *et al*).

Ramos Hernanz *et al*. (2010) proposed a review of the main characteristics and parameters that have to be considered while modelling a photovoltaic module. Matlab based photovoltaic model, which illustrates the PV cell and module was presented. The created model has been based on prior studies conducted by Walker, Akihiro Oi and Gonzalez-Longatt. I-V and P-V curves have been measured based on the information of the former models. The results were compared to each other. Also, the maximum power point (MPP) of all the models was calculated. The simulated data were validated with the commercial PV module of Mitsubishi PV-TD1185MF5 experimental data. Four possibilities of solar cell modelling has been analyzed (Fig. 6) and observed that Walker, Gonzalez-Longatt and the generic one gave similar results, whereas Akihiro Oi model always gave inferior values of the MPP.

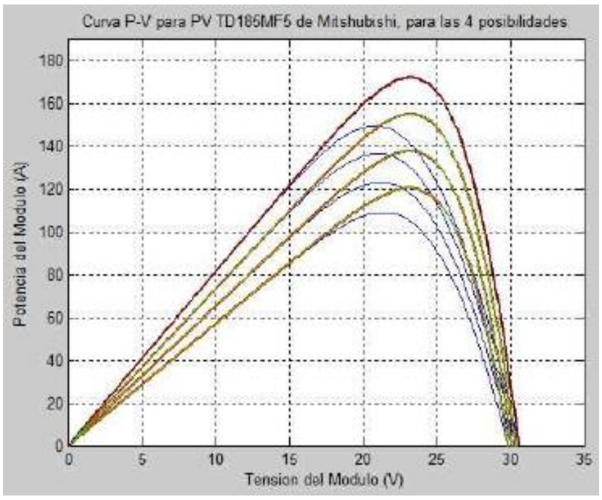

Fig. 6: P-V curve at constant ambient temperature (Courtesy: Ramos Hernanz *et al*).

Estimation of the electrical behavior of the solar cell with respect to changes in the environmental parameters of temperature and irradiance based on the circuit-based simulation model was proposed by Francisco M. Gonzalez-Longatt (2005). Based on the Shockley diode equation they presented an accurate photovoltaic module electrical model. Simulation tool used to implement the general model was Matlab script file which accepts the variable inputs of solar irradiance and temperature and produces the output of I-V characteristic. To evaluate, a particular typical Solarex MSX60 solar panel was used and results were compared.

MSX60 solar panel manufacturer's published curves were used for the validation and comparison. Authors took the discrete data points directly from the manufacturer's published curves as shown in Fig. 7. Outcomes from the developed Matlab™ model had shown the excellent correspondence to the manufacturer's published curves. Modelling and simulation of grid connected photovoltaic system for Malaysian climate has been done by Rahman *et al*. (2010). Influence of three parameters of ambient temperature, solar irradiance and clearness index on the outdoor performance of poly-crystalline (poly-Si) PV modules has been studied in this paper. Specifically, impact of clearness index (0.45, 0.5 and 0.55) on the output energy of the BIPV system in Malaysia has been considered. Results were simulated via Matlab/Simulink and compared with the actual monitored data using 45.36 kWp capacity PV system located at Pusat Tenaga Malaysia (PTM), Bangi, Selangor. They concluded that in addition to the ambient temperature and solar irradiance, clearness index is also a critical determinant while estimating the output energy of the solar PV system.

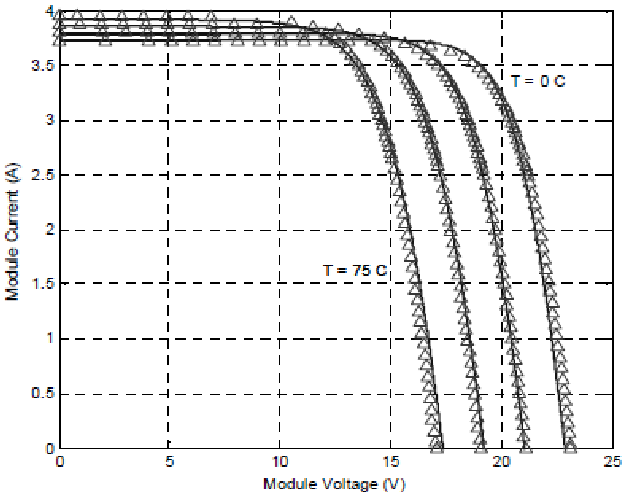

Fig. 7: Matlab model I-V curves for various temperatures (MSX-60, G = 1 Sun, T = 0, 25, 50 and 75°C) (Courtesy: Francisco M. Gonzalez-Longatt).

The implementation of a generalized photovoltaic model using Matlab/Simulink software package has been presented by Huan-Liang Tsai *et al*. (2008). Generalized PV model represents PV cell, module and array. User-friendly icon and a dialog box like Simulink block libraries have been designed in this proposed model. Together with power electronics for a maximum power point tracker, this aid to simulate and analyze the generalized PV model easily. The electrical characteristics of the PV model such as output current, power were simulated by taking in to account of solar irradiance and cell temperature. For a sample day, output power has been statistically simulated as shown in Fig. 8 for various output voltages.

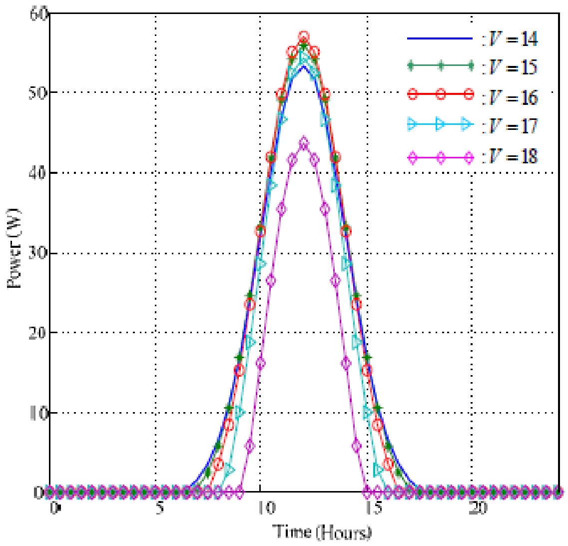

Fig. 8: Power characteristics during a sample day for different voltage (Courtesy: Huan-Liang Tsai *et al*).

A simulation and characterization tool which can be used to evaluate the electrical performances of photovoltaic (PV) panels was described by Adamo *et al*. (2009). Single diode model was used for estimating the electrical parameters of a PV panel. I-V characteristic changes with environmental parameters such as temperature and irradiance were then predicted. Matlab script was utilized to test the model which yields the I-V and P-V characteristics of the PV panel. A simple volt-ammeter method was used by these authors to collect the real environmental data for validation purposes. The model has been validated against an experimentally characterized Istar Solar IP10P PV panel. Electrical characteristics of this typical 10 Wp PV panel were used for estimation and testing. Comparison between the measured I-V and P-V characteristics has been made by these authors using the values predicted by the model in two cases: initial model - first estimation of series and shunt resistance parameters (R_{s0} and R_{sh0}); best-fit model - resistances determined by means of a best-fit over the measured data and the results were displayed as graphs. Comparison between the measured I-V characteristic, and the characteristic obtained with the initial model and the best-fit model is shown in Fig. 9.

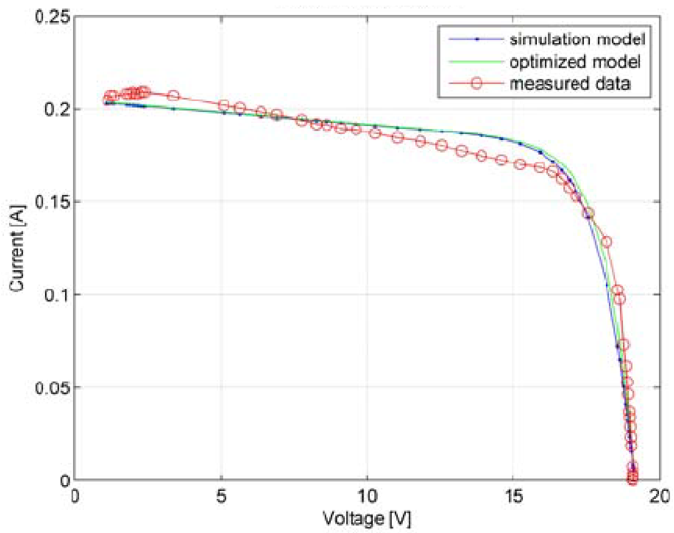

Fig. 9: I-V characteristic curve for IP10P at G = 300 W/m^2 and T = 27^{o}C (Courtesy: Adamo *et al*).

The general outline of a simulation model to size and assess the performance of the PV installation has been presented by Benatiallah *et al*. (2006). DELPH5 programming language was used by these authors. The developed program allows the user to determine the performance of the PV installation at any moment via comparing the PV electric energy produced and the required consumption load. It also aids to optimize the system relative to the factor of time. Power output of the day has been determined by these authors according to the characteristics of the various components of the installation, of local temperature and solar irradiation data as shown in Fig. 10.

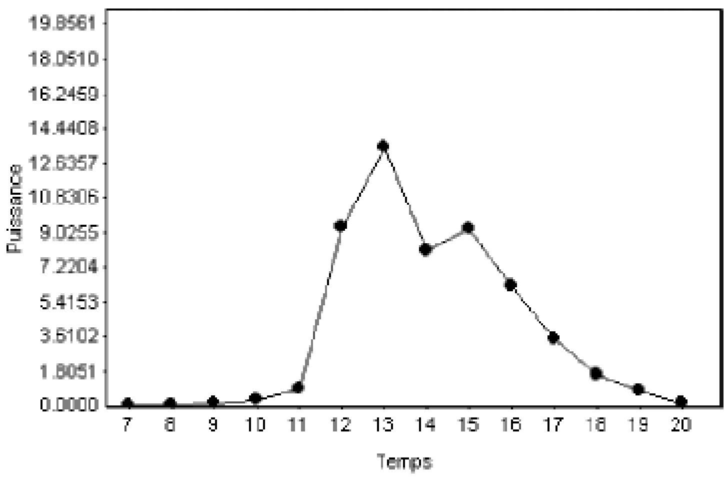

Fig. 10: Installation power output as a function of time (Courtesy: Benatiallah *et al*).

Kashif Ishaque *et al*. (2011) proposed a Matlab Simulink simulator for photovoltaic (PV) systems utilizing the improved two diode model for the representation of PV cells. They estimated the shunt resistance (R_p) and series resistance (R_s) by an efficient iteration method and also reduced the input parameters to four in order to lessen the computational time. Also, authors have done large array simulations with interfacing of MPPT algorithms and actual power electronic converters and results from the simulator were shown. The simulator accuracy was verified with five PV modules of different types (multi-crystalline, mono-crystalline and thin-film) from various manufacturers. They found a close agreement with the theoretical predictions. Sample result of I-V curves of R_s and proposed two-diode model of the Kyocera KC200GT PV module for several temperature levels @ 1 kW/m^2 is shown Fig. 11.

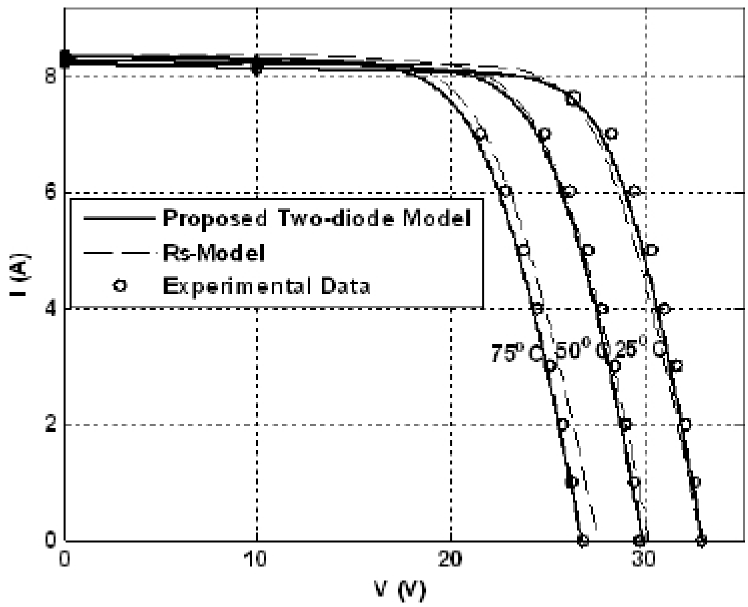

Fig. 11: I-V curves of R_s and proposed two-diode model (Courtesy: Kashif Ishaque *et al*).

Comparative study of various mathematical modeling of PV array has been done by Satarupa Bal *et al*. (2012). Ideal single diode model (ISDM), single diode model (SDM), two diode model, simplified single diode model (SSDM) and the improved single diode model (ImSDM) were utilized by these authors in order to carry on the comparative analysis. Modelling and simulation was done in Matlab/Simulink environment. Best model has been selected based on the maximum power point (MPP) tracking and root mean square deviation (RMSD) from the experimental data comparisons (Table 2). Authors concluded that simplified single diode model has comparable accuracy levels with less simulation time.

Table 2: RMSD and MPP values (Source: Satarupa Bal *et al*).

Equivalent Circuit	RMSD (A)	MPP
Ideal single diode	0.089	16.1 (V), 1.42 (A)
With R_s (SSDM)	0.068	16.68 (V), 1.51 (A)
With R_s and R_{sh} (SDM)	0.056	16.29 (V), 1.46 (A)
With two-diode	0.0547	16.31 (V), 1.47 (A)
With improved single diode	0.053	16.30 (V), 1.47 (A)

Salih Mohammed Salih *et al*. (2012) evaluated the performance of the photovoltaic models based on a solar model tester. One diode equivalent circuit was employed and the I-V/P-V characteristics of 130 W (Solara PV) and 100 W (Sunworth PV) were calculated using the Matlab software. Influence of the series resistance, solar irradiance level, operating temperature and diode ideality factor on the model performance were studied and compared with the nameplate of each tested model. Theoretically, authors tested the PV model using the Matlab software and practically using a solar model tester. They concluded that in order to calculate the PV model parameters, solar model tester is more appropriate than a diode equivalent circuit model. Similar study has also been carried out by Rodrigues *et al*. (2011) Temperature dependence, solar radiation change, diode ideality factor and series resistance influence had been assessed using Matlab/Simulink. In addition, they compared the ideal single diode model and single diode model with series resistance in simulating the I-V and P-V characteristics. Single diode model with series resistance offers a more realistic behavior of solar cell as per the results and conclusions drawn by this author. Tjukup Marnoto *et al*. (2007) developed the mathematical model to predict the performance characteristics of multi-crystalline photovoltaic modules. Set of new equations pertaining to fitting-parameter (a), photo generated current (I_L), saturated current (I_0) and the maximum power point had been presented and discussed. The characteristics of PV modules were simulated graphically. Results were compared with the experimental grid interactive PV system of 5 kWp capacity situated at Solar Energy Research Institute (SERI) of University Kebangsaan Malaysia (UKM) for validation purposes. They concluded that the developed mathematical model in this research were simple and qualified using only the temperature and solar radiation data, and could able to predict the performance and maximum power point of PV module. The prediction results of maximum power point in several solar radiation levels and temperature at 40^{o}C is shown in Fig. 12.

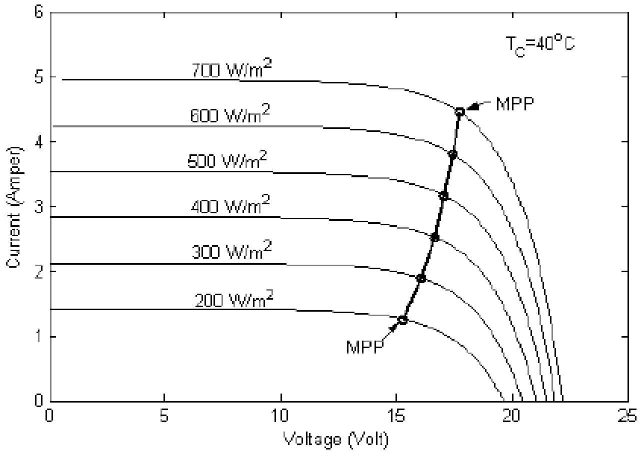

Fig. 12: I-V characteristic and maximum power point of a PV module (Courtesy: Tjukup Marnoto *et al*).

Conclusion:

In light of global aim in reducing carbon footprint from fossil fuel based electricity generation, there has been an increasing interest in the dependence of solar energy as an alternative way to produce electricity nowadays. The knowledge on the prediction of the power output or performance of solar cells can be beneficial when it comes to validating actual power measurements and forecasting the output at a specific location for a period of time without any solar module installation. In this paper, different mathematical models, equivalent circuits and simulation tools that have been utilized by the prior researchers for predicting the electrical characteristics of solar photovoltaic cells were reviewed in detail. It is envisaged that this article will be beneficial for engineers, power electronics designers, PV professionals and researchers who need the related review of literatures to model and simulate photovoltaic arrays.

REFERENCES

Adamo, F., F. Attivissimo, A. Di Nisio, A.M.L. Lanzolla and M. Spadavecchia, 2009. Parameters estimation for a model of photovoltaic panels. Proc. 19th IMEKO World Congress, Fundamental and Applied Metrology, pp: 964-967.

Andreea Maria Neaca and Mitica Iustinian Neaca, 2009. Modeling photovoltaic systems for AC appliances. Journal of Electrical and Electronics Engineering, 2(2): 58-63.

Benatiallah, A., R. Mostefaoui, M. Boubekri and N. Boubekri, 2006. A simulation model for sizing PV installations. Desalination, 209(3): 97-101.

Chenni, R., M. Makhlouf, T. Kerbache and A. Bouzid, 2005. A Detailed Modelling Method for Photovoltaic Cells. Energy (Elsevier), 32(9): 1724-1730.

Francisco M. Gonzalez-Longatt, 2005. Model of Photovoltaic in Matlab™. 2do Congreso Iberoamericano de Estudiantes de Ingeniería Eléctrica. Electrónica y Computación (II CIBELEC 2005), pp: 1-5.

Hamdaoui, M., A. Rabhi, A. El Hajjaji, M. Rahmoun and M. Azizi, 2009. Monitoring and control of the performances for photovoltaic systems. Proc. IREC'09, International Renewable Energy Congress (IREC), pp: 69-71.

Huan-Liang Tsai., Ci-Siang Tu and Yi-Jie Su, 2008. Development of Generalized Photovoltaic Model Using MATLAB/SIMULINK. Proceedings of the World Congress on Engineering and Computer Science (WCECS).

Kashif Ishaque., Zainal Salam and Hamed Taheri, 2011. Accurate MATLAB Simulink PV System Simulator Based on a Two-Diode Model. Journal of Power Electronics, 11(2): 179-187.

Lasnier, F and T. G. Ang, 1990. Photovoltaic engineering handbook. New York: Taylor & Francis.

Marcelo Gradella Villalva., Jonas Rafael Gazoli and Ernesto Ruppert Filho, 2009. Modeling and circuit based simulation of photovoltaic arrays. Power Electronics Conference (COBEP'09), pp: 1244-1254.

Mrabti, T., M. El Ouariachi, F. Yaden, Ka. Kassmi and K. Kassmi, 2010. Characterization and Modeling of the Electrical Performance of the Photovoltaic Panels and Systems. Journal of Electrical Engineering: Theory and Application, 1(2): 100-110.

Rahman, H.A., K.M. Nor, M.Y. Hassan, S. Thanakodi, M.S. Majid and F. Hussin, 2010. Modeling and Simulation of Grid Connected Photovoltaic System for Malaysian Climate Using Matlab/Simulink. 2010 IEEE International Conference on Power and Energy (PECon), pp: 935-940.

Ramos Hernanz, J.A., J.J. Campayo Martin, I. Zamora Belver, J. Larranaga Lesaka, E. Zulueta Guerrero, E. Puelles Perez, 2010. Modelling of Photovoltaic Module. International Conference on Renewable Energies and Power Quality (ICREPQ'10).

Rodrigues, E.M.G., R. Melicio, V.M.F. Mendes and J.P.S. Catalao, 2011. Simulation of a Solar Cell considering Single-Diode Equivalent Circuit Model. In: ICREPQ'11 International conference on renewable energies and power quality, pp: 1-5.

Rustemli, S and F. Dincer, 2011. Modeling of Photovoltaic Panel and Examining Effects of Temperature in Matlab/Simulink. Elektronika Ir Elektrotechnika (Journal of Electronics and Electrical Engineering), 3(109): 35-40.

Salih Mohammed Salih., Firas Fadhil Salih, Mustafa Lateef Hasan and Mustafa Yaseen Bedaiawi, 2012. Performance Evaluation of Photovoltaic Models Based on a Solar Model Tester. I.J. Information Technology and Computer Science, 4(7): 1-10.

Satarupa Bal., Anup Anurag and B. Chitti Babu, 2012. Comparative Analysis of Mathematical Modeling of Photo-Voltaic (PV) Array. India Conference (INDICON), 2012 Annual IEEE, pp: 269-274.

Surya Kumari, J and Ch. Sai Babu, 2012. Mathematical Modeling and Simulation of Photovoltaic Cell using Matlab-Simulink Environment. International Journal of Electrical and Computer Engineering (IJECE), 2(1): 26-34.

Tjukup Marnoto., Kamaruzzaman Sopian, Wan Ramli Wan Daud, Mohamad Algoul and Azami Zaharim, 2007. Mathematical Model for Determining the Performance Characteristics of Multi-Crystalline Photovoltaic Modules. Proc. of the 9th WSEAS Int. Conf. on Mathematical and Computational Methods in Science and Engineering, pp: 79-84.

Tomas Skocil and Manuel Perez Donsion, 2008. Mathematical Modeling and Simulation of Photovoltaic Array. Proceedings of the International Conference on Renewable Energy and Power Quality 2008 (ICREPQ'08).

Walker, G.R., 2001. Evaluating MPPT Converter Topologies using a MATLAB PV Model. Journal of Electrical & Electronics Engineering, Australia, 21(1): 49-56.

Wei Zhou., Hongxing Yang and Zhaohong Fang, 2007. A novel model for photovoltaic array performance prediction. Applied Energy, 84(12): 1187-1198.

Yang Gang and Chen Ming, 2009. LabVIEW Based Simulation System for the Output Characteristics of PV Cells and the Influence of Internal Resistance on It. WASE International Conference on Information Engineering (ICIE), pp: 391-394.