ISSN 0003-701X, Applied Solar Energy, 2022, Vol. 58, No. 1, pp. 86–94. © Allerton Press, Inc., 2022.
Russian Text © The Author(s), 2022, published in Geliotekhnika, 2022, No. 1, pp. 109–119.

Performance Evaluation of Different Models of PV Panel in MATLAB/ Simulink Environment

Khamma Kanwar[a], * and Dr. Jayashri Vajpai[a]

[a] *Electrical Engineering Department M. B. M. University, Rajasthan, Jodhpur, 342011 India*

**e-mail: kkjoya.jnvu@gmail.com*

Received December 7, 2021; revised February 25, 2022; accepted April 29, 2022

Abstract—A review of literature in the area of modeling and simulation of solar photovoltaic (PV) systems shows that there are a number of models that are equivalent to each other in terms of matching of performance characteristics with an ideal PV panel of the same rating. Researchers have different opinions regarding the simulation of PV panel models but none of them suggest which model is the best for implementation in less time and offers the flexibility to change the model parameters for further analysis of PV panel behavior. Hence, the starting phase of research consumes more time to select the best model of PV panel for simulation and analysis. This paper aims to help researchers to get an idea about the different types of simulation models of PV panels that are described in the literature or available in MATLAB software and save time for model selection when starting their research work. In this paper, four different types of PV Simulink models have been selected for study from the ones available in the literature and one PV model has been proposed. The datasheet parameters of PV panel KC200GT manufactured by Kyocera Corporation, Japan are used as a reference for all five Simulink models. All the five models were implemented in MATLAB software and a comparison of their output electrical characteristics has been carried out for the same operating conditions. It was found that the performance of the proposed model is comparable with the best ones available in the literature, while the time required for its simulation is lesser. The importance of this study lies in improving the accuracy of modeling and simulation process of PV systems and in serving as a guideline for beginners in this area of research.

Keywords: photovoltaic systems, PV model, MATLAB/Simulink models, performance of PV panels, modeling of PV panels

DOI: 10.3103/S0003701X22010078

INTRODUCTION

In the recent decades, solar photovoltaic (PV) systems have become the fastest-growing alternative source of energy with an installed capacity of 653 GW globally and 45 GW in India as on. These systems are environmentally friendly, have a long life, and require less maintenance.

The output characteristics of PV cells are nonlinear and fluctuate with the amount of solar radiation, cell temperature, series and parallel resistance [1]. They can be modeled on the basis of Shockley equation. This results in a five parameters model that includes a current source, diode, ideality factor, series resistance R_s, and shunt resistance R_p. Both single diode and double diode models are commonly used to simulate PV characteristics. The efficiency of the solar energy conversion is directly related to the maximum power extraction (MPP) from the PV system. In a practical PV cell, series resistance is associated with the losses in the current path due to the metal grid, contacts, and current collecting bus. Likewise, shunt resistance is included to represent the losses associated with a small leakage of current through a resistive path in parallel with the built-in device through the *p*–*n* junction. The shunt resistance is larger than the series resistance.

These models have been simulated by a large number of researchers by using dif-ferent software. MATLAB/Simulink has turned out to be the most popular among them due to its ease of implementation. This paper, hence, focuses on four such models.

Over the last decade, many researchers have studied and simulated the characteristics of PV panel using both the programming approach and the simulation ap-proach, thus developing models in the form of MATLAB M-File and MATLAB/Simulink. Simulation of these models have been carried out under differ-ent temperature and irradiance conditions and reported by several authors [2–6]. A brief survey of the important ones among these is presented here.

Mohan and Dhinakaran [7] have implemented a mathematical equation based solar PV cell model. The electrical characteristics of the proposed model under the selected physical and environment conditions were obtained by simulation in MATLAB/Simulink. Then an experiment was conducted to validate the simulated data. However, the results obtained from the experiment do not match the result obtained from the simulation.

Villalva et al. [8] have developed a mathematical model to find out the best $I–V$ equation for PV array by adjusting the $I–V$ curve at three points, viz., open-circuit voltage (V_{oc}), Maximum power point, and short circuit current (I_{sc}), taken from the commercial array datasheet. This paper provides the allnecessary information to easily develop a single-diode photovoltaic array model for analyzing and simulating a PV array. It has also presented two circuit models that can be used to simulate PV arrays with any of the circuit simulators.

Nguyen and Nguyen [9] have explained the step-by-step procedure of mathematical modeling of PV array in MATLAB/Simulink under different environmental conditions. The output characteristics of the simulation model have been found to match the characteristics of DS-100M solar panel. It has been concluded that the solar irradiation, temperature and shunt resistance have a significant effect on output power, current and voltage.

AbdelHady [10] has used the inbuilt PV array and developed a MATLAB/Simulink model that evaluates the system performance when it is tied either with the local grid or the national grid. This paper shows that economical savings estimated under the condition when system is connected to the national grid are exponentially high as compared to the saving of the real system when feeding the local grid.

Veerachary [11] has developed circuit-oriented model for the PV source using PSIM software and generated $V–I$ and $P–V$ characteristics of PV source for different solar insolation. The results have been compared with the experimentally measured characteristics. Since simulated characteristics were in close agreement with those obtained from the experiments, this validated the developed models as well as the modeling method.

G.E. Ahmad et al. [12] have introduced a theoretical analysis of the performance of photovoltaic modules under different meteorological conditions with the help of TRNSYS simulation program. It has included parameters like short circuit current, open circuit voltage, maximum output power, $I–V$ and $P–V$ characteristics, and efficiency. Then a comparison is carried out in between experimental and theoretical results. It shows the good results at different meteorological conditions, tilt angles, and orientations. The developed model is capable to predict the temperature, $I–V$ and $P–V$ curves, and other output parameters of PV modules at different conditions.

Thus, lots of research work has been done on different PV models using MATLAB and other software. However, research is yet to identify the model that gives the best response. The purpose of this paper is to present a brief idea about the different types of PV models available in the literature and propose a new the best model by including the good features from different models, in order to obtain the best performance according to their electrical characteristics. It deals with the modeling and simulation of five different models of the standalone PV system that includes four from literature and one proposed in this paper. These models have been simulated in MATLAB software and then a comparison of electrical characteristics is carried out to validate that the performance and ease of implementation of the proposed model is the best among these models.

PROBLEM FORMULATION AND METHODOLOGY

The implementation of the mathematical model of PV panel [8] has been carried out in MATLAB/Simulink software using the tools and user defined functions. PV panel KC200GT manufactured by Kyocera Corporation, Japan that has a rating of 32.9 V, 200 W is selected for mathematical analysis and modeling in this study, as this has been widely reported in published literature. The following Table 1 shows the datasheet parameters of 200 W PV array model KC200GT.

The simulation of the selected and proposed models of PV panel and comparative analysis of their electrical characteristics with respect to parameters as mentioned in the manufacturer datasheet has been carried out as presented in the next sections.

The process of mathematical modeling of PV cell is primarily defined on the basis of the widely used five parameters model [13]. The equivalent circuit of PV cell [8] that consists of a current source, a diode, ideality factor, a series resistance, R_s and a parallel resistance, R_p. The diode is connected in anti parallel with the photo current source and represents the theoretical model of the ideal PV cell as shown in Fig. 1.

The output current of this model, on the basis of Shockley diode equation, may be expressed as follows [8]:

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + IR_s}{V_t a}\right) - 1\right] - \frac{(V + IR_s)}{R_p}, \qquad (1)$$

where I_{pv}: photocurrent (A), I_0: diode saturation current (A).

Thermal voltage of the array:

$$V_t = N_s kT/q, \qquad (2)$$

N_s: Number of cells connected in series

q: Electron charge ($1.60217646 \times 10^{-19}$ C)

Table 1. Specification of the Kyocera PV panel KC200GT selected for modeling

Model	KC200GT
Maximum power, W	200.143
Open circuit voltage V_{oc}, V	32.9
Short circuit current $I_{sc} \approx I_{pv}$, A	8.21
Voltage at maximum power point V_{mp}, V	26.3
Current at maximum power point I_{mp}, A	7.61
Diode saturation current I_0, A	9.825×10^{-8}
Open-circuit voltage / temperature coefficient K_V, V/K	–0.1230
Short-circuit current/ temperature coefficient K_I, A/K	0.0032
Ideality constant (a)	1.3
Shunt resistance R_p, Ω	415.405
Series resistance R_s, Ω	0.221
Number of cells in series N_s	54

k: Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)

T: Module operating temperature (K)

a: Diode ideality constant

R_s: Series resistance(ohm) and

R_p: Parallel resistance (ohm).

The photocurrent of the PV cell depends linearly on the solar irradiation and temperature according to the following equation:

$$I_{pv} = (I_{pv,n} + K_I \Delta_T)\frac{G}{G_n}, \tag{3}$$

where $I_{pv,n}$: photo current at the nominal condition, generally considered to be defined for the standard values of temperature at 25°C and irradiation at 1000 W/m^2.

$$\Delta_T = T - T_n, \tag{4}$$

T_n: Nominal temperatures (K),

G: Irradiation on the device surface (W/m^2), and

G_n: Nominal irradiation.

The diode saturation current is described by:

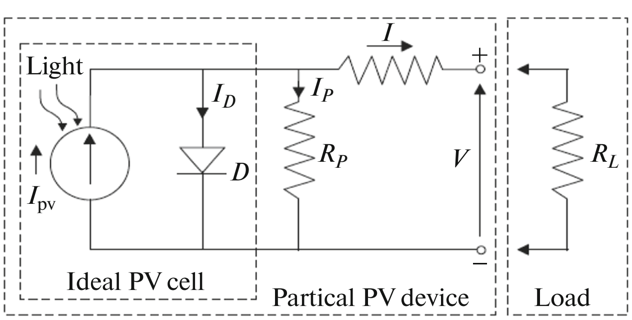

Fig. 1. Equivalent model of a PV cell [8].

$$I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp\left(\dfrac{V_{oc,n} + K_V \Delta_T}{a V_t}\right) - 1}, \tag{5}$$

$I_{sc,n}$: Short circuit current at nominal condition (A)

$V_{oc,n}$: Open circuit voltage at nominal condition (V)

K_V: Open circuit voltage/temperature coefficient K_V [V/K]

K_I: Short circuit current/temperature coefficient K_I [A/K].

The parameters R_p, R_s, a, and I_0 are specific to different commercial PV array. They can be calculated from the manufacturer data sheet values tested at the Standard Test Conditions (STC) or reference Point which is 1000 W/m^2 solar irradiation and 25°C cell temperature. Using these equations the mathematical model of PV panel at STC has been developed in this paper and simulation has been done for obtaining the I–V and P–V characteristics.

SIMULATION OF THE MODELS UNDER CONSIDERATION

The performance of the models considered in this paper has been compared by simulating them one by one in the MATLAB/Simulink platform by using version 2016a of the software. The simulation of all the four selected and proposed models were carried out for PV panel model KC200GT at STC conditions. The simulation of these models is discussed in the next subsection.

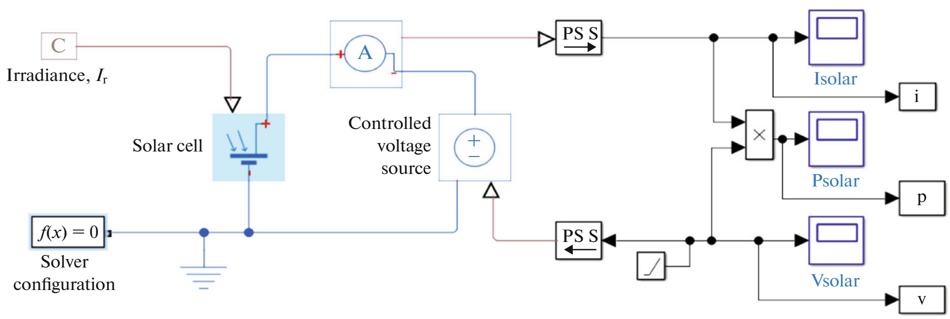

Fig. 2. Simulation model based on solar cell block.

SIMULATION BASED ON SOLAR CELL BLOCK AVAILABLE IN MATLAB/SIMULINK

An inbuilt solar cell block is available as a solar cell current source in Simscape Electronics Library in the MATLAB software. The characteristics of the solar cell block can be parameterized by

(1) Equivalent circuit parameters using five parameters model.

(2) Short circuit current and open circuit voltage using five parameters model.

(3) Equivalent circuit parameters using eight parameters model.

After selecting either eight parameters-based model or five pararmeters based model, the required values of parameters can be assigned to the model.

Solar cell based demo example is available in the Device Characteristics, Simscape Electronics to generate the P–V curve. The same has been implemented by setting the parameters according to KC200GT datasheet as shown in Table 1. It has an option of selecting either eight parameter model or a five-parameter model. If the five-parameter model is selected, then this block can be parameterized in terms of the short-circuit current and open-circuit voltage or in terms of the equivalent circuit model parameters. The model is simulated as shown in Fig. 2.

On simulation, this model performed in unsatisfactory manner for the KC200GT parameters as shown in Fig. 3. But, surprisingly even after giving all the necessary data it gives smooth I–V and P–V characteristics for V_{oc} above 200 V and hence may be useful for such ratings.

SIMULATION BASED ON PV ARRAY BLOCK AVAILABLE IN MATLAB/SIMULINK

The simulation of MATLAB/Simulink inbuilt PV array block shown in Fig. 4 was carried out next. It shows the replica of ideal PV array characteristics. There are a large number of options of PV panels from which the required panel can be selected. It takes the values of N_s, V_{oc}, I_{sc}, V_{mp}, I_{mp} maximum power, temperature coefficients of V_{oc} and I_{sc} automatically from the database after selecting the panel. Also, there is a provision to select User defined panel, where the desired specifications like N_s, V_{oc}, I_{sc}, V_{mp}, I_{mp} maximum power, temperature coefficients of V_{oc} and I_{sc} can be defined manually.

Figure 5 shows the I–V and P–V characteristics of PV array block for the KC200GT model and it can be observed that it matches the data of the given PV specification. The main drawback of this block is that it computes the five corresponding model parameters (I_{pv}, I_0, A, R_{sh}, R_s) using an optimization function. Hence, the performance of the inbuilt PV array block

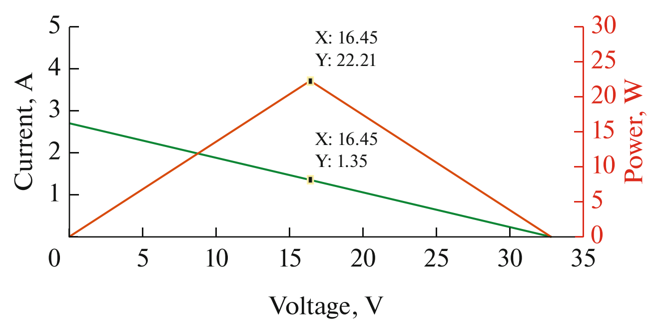

Fig. 3. Output I–V and P–V characteristics of a solar cell block.

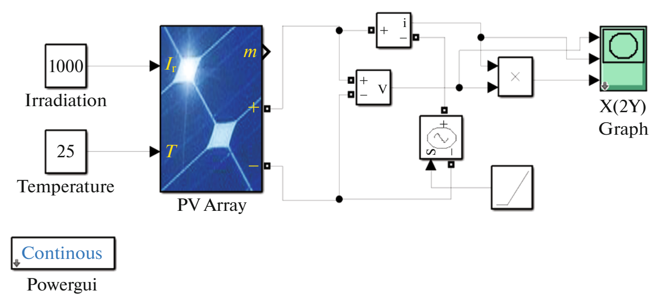

Fig. 4. Simulation model based on built PV array block.

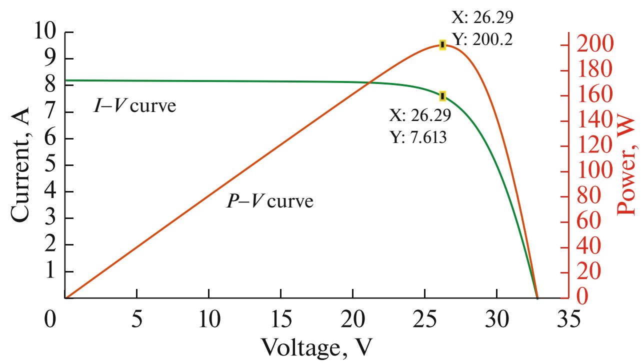

Fig. 5. Output *I*–*V* and *P*–*V* characteristics of built PV array block.

cannot be analyzed with the variation of these parameters, which is a great limitation.

SIMULATION BASED ON MOHAN AND DHINAKARAN PV MODEL

Mohan and Dhinakaran [7] have suggested a new simulation model of solar PV cell based on mathematical equations in MATLAB/Simulink. This model emulates the PV Cell behavior at ambient environment conditions. They have reported the results of an experimental test conducted to validate the simulated data. The results obtained from the experiment do not match with the results obtained by the simulation. The simulation of the developed model was carried out with datasheet parameters of KC200GT in MATLAB/Simulink as shown in Fig. 6.

Figure 7 shows that the *I*–*V* and *P*–*V* characteristics of the developed model match the specifications but it requires more components for describing the PV cell behavior. These include PS simulink converter, diode, simulink PS converter, variable resistor etc. Hence, more time is required in designing this simulation model as compared to the previous ones.

SIMULATION BASED ON M.G. VILLALVA ET AL. PV MODEL

Villalva et al. [8] have developed an easy and accurate method of modeling PV arrays that can be simulated with any circuit simulator. The author has included diode saturation current I_0 which depends on the temperature. The results obtained are accurate and the model permits adjustment of the *I*–*V* curve exactly at three-point i.e. the open circuit voltages, short circuit current, and maximum power point. The simulation of the developed model is carried out in MATLAB/Simulink in this paper, so that its performance can be compared with the other models. The model was simulated as shown in Fig. 8.

Figure 9 shows the *I*–*V* and *P*–*V* characteristics of this model. The *I*–*V* curve matches the ideal characteristics at three-point i.e. the open circuit voltages, short circuit current, and maximum power point. The limitation of this model is that two separate resistors are required for representing the R_s and R_p. Moreover, the procedure for implementing the model is not clearly explained.

PROPOSED MODEL

The study of performance characteristics of PV models discussed and simulated in section 3 of this paper, clearly shows that these models are not adequate for applications where the flexibility of tuning of some parameters in the system is required. Nguyen and Nguyen have presented a step-by-step procedure for the simulation of PV circuit model in MATLAB/Simulink. This provides an accurate, reliable, and easy-to-tune model of PV array [9]. As mentioned in the previous subsection, M.G. Villalva has proposed a mathematical formulation of diode saturation current I_0 which depends on the temperature and the results obtained on simulation of this model as shown in Fig. 9 and Table 2 are accurate. Using Villalva model equation and Nguyen procedure, a hybrid model of PV array

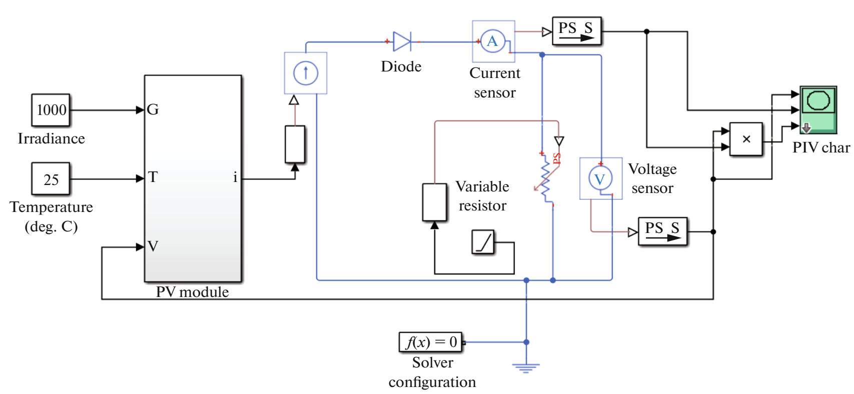

Fig. 6. Simulation of Mohan and Dhinakaran PV model [7].

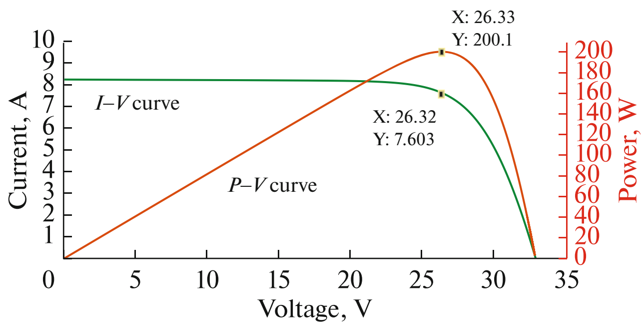

Fig. 7. Output I–V and P–V curves of Mohan and Dhinakaran PV model.

has been developed in this work. It is expected to be advantageous in investigating the solar PV array operation from different angles, such as with variation of physical parameters, series and shunt resistance, ideality factor, etc. This model will be useful for analyzing the effect of change of different conditions as varying temperature, irradiation, and especially partial shadow effect.

Figure 11 shows the I–V and P–V characteristics of the proposed model, it is suitable for implementation when the simulation has to be carried out in less time and offers the flexibility to change the parameters for further analysis of PV panel behavior.

MODELING OF THE RECOMBINATION PHENOMENA

The simulation model proposed in section 4 has been developed on the basis of single diode, five parameters mathematical model, expressed by the Shockley diode equation. This model can be further improved to include the effect of recombination phenomena, which causes losses due to space charge. For this purpose, the proposed model has been modified to include the two-diode model. This is done by incorporating an additional Shockley diode equation, as expressed in Eq. (6).

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + IR_s}{V_t a}\right) - 1\right] - I_{01}\left[\exp\left(\frac{V + IR_s}{V_t a_1}\right) - 1\right] - \frac{(V + IR_s)}{R_p}, \quad (6)$$

where I_{01} = saturation current of second diode (A), a_1 = ideality constant of second diode.

The simulation is carried out by using MATLAB/Simulink model as shown in Fig. 10 at STC conditions. The electrical output characteristics of this model are shown in Fig. 12.

It is observed that the output maximum power reduces due to the effect of use of two diodes in the proposed model. The corresponding output voltage and current have also reduced.

SIMULATION RESULTS

After the detailed comparative study of all existing PV circuit models, simulation was carried out while maintaining the prescribed datasheet parameters for the KC200GT model. The five different models of PV panel compared by simulation are as follows:

(i) The first model is implemented using solar cell block-based demo example which is available in MATLAB Software.

(ii) The second model is simulated based on built PV array block which is already available in MATLAB.

(iii) The simulation of the third model is carried out using the Mohan and Dhinakaran proposed model.

(iv) The fourth model is implemented using the M.G. Villalva et al. proposed model.

(v) With the help of Villalva equation and Nguyen procedure step the PV model is proposed and implemented as the fifth model.

The study highlights that proper selection of model may further improve the performance of PV panel and facilitates selection of proper model as a stepping stone for further research. All these models were implemented in MATLAB/Simulink and a comparison of

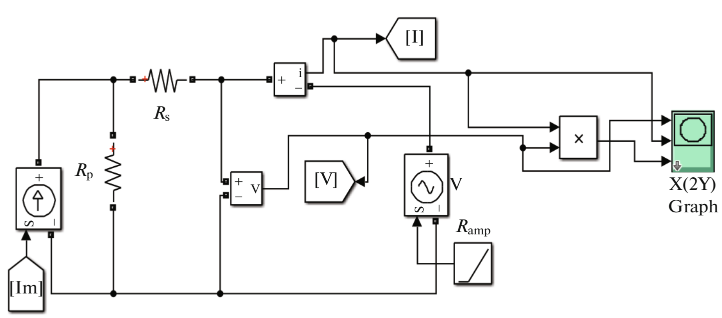

Fig. 8. Simulation of M.G. Villalva et al. PV model [8].

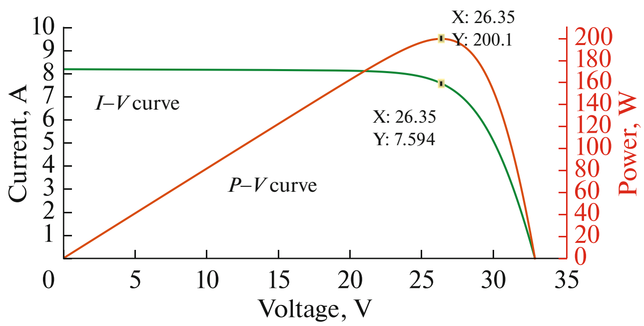

Fig. 9. Output *I*–*V* and *P*–*V* curves of M.G. Villalva et al. PV Model.

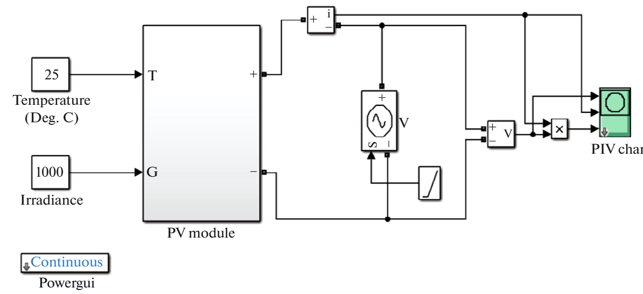

Fig. 10. Proposed PV model.

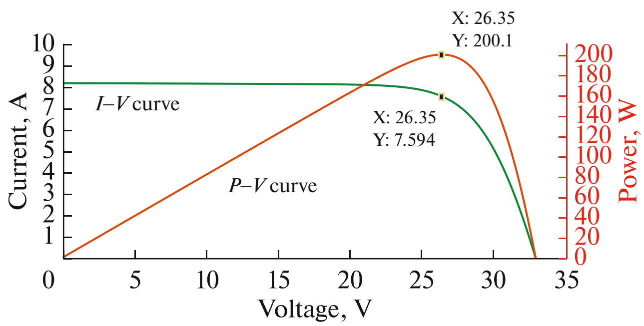

Fig. 11. Output *I*–*V* and *P*–*V* curves of proposed PV model.

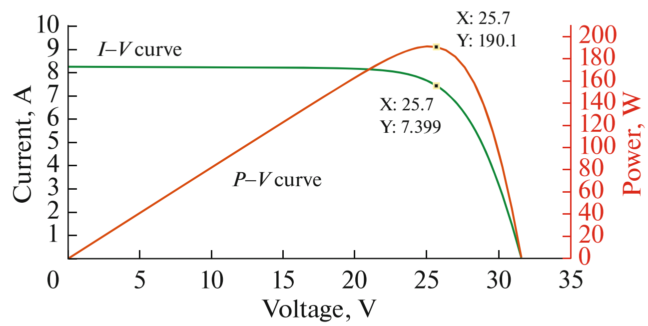

Fig. 12. Output *I*–*V* and *P*–*V* curves of proposed PV model with recombination phenomena.

output voltage, current, and power is carried out as shown in the following Table 2.

The values of performance parameters are as shown in Table 2, which clearly depicts the relative merits of models. It can be inferred that the results obtained from simulation of the first model based on the solar cell block of MATLAB/Simulink do not match with short circuit current and open circuit voltage as per the datasheet parameters. The values obtained from the simulation of the remaining four different PV models closely match the parameters indicated in the manufacturer's datasheet of KC200GT. But the proposed model was shown at S.

Table 2. Electrical characteristics of selected models of PV panel

S. No.	Types of PV circuit model	Simulation inputs: open circuit voltage $V_{oc} = 32.9$ V, Short circuit current $I_{sc} \approx I_{pv} = 8.21$ A		
		voltage, at maximum power V_{mpp},V	current, at maximum power I_{mpp}, A	maximum power, W
1	Solar cell block available in MATLAB/Simulink	16.45	1.35	22.21
2	Inbuilt PV array block in Simscape	26.29	7.613	200.2
3	Model proposed by Mohan and Dhinakaran	26.33	7.603	200.1
4	Model proposed by M.G. Villalva et al.	26.35	7.594	200.1
5	(i) Proposed model with single diode	26.35	7.594	200.1
	(ii) Proposed model with two diodes	25.7	7.399	190.1

Table 3. Comparative analysis of selected models of PV panel (merits and demerits)

Parameters	Models				
	solar cell block available in MATLAB/ Simulink	inbuilt PV array block available in Simscape	model proposed by Mohan and Dhinakaran	model proposed by M.G. Villalva et al.	proposed model with single diode
Ease of implementation	High	High	Low	Low	High
No. of components required	Less	Less	More	More	Less
Flexibility of tuning of parameters	Not possible for some parameters like maximum power, V_{mp} and I_{mp}	Not possible for some parameters like I_{pv}, I_0, A, R_{sh}, R_s	Possible for all parameters	Possible for all parameters	Possible for all parameters
Performance	Poor	Very good	Very good	Very good	Very good

No. 4 requires less time for implementation and simulation in comparison to others.

CONCLUSIONS

Modeling, simulation, and analysis of different models is an important primary phase in the design, research and implementation of a PV system. In this paper, an attempt has been made to compare four PV panel models by simulating their performance on MATLAB/Simulink platform. A new methodology of modeling has also been proposed on the basis of the experience gained in this process and the fifth model has been developed and simulated. The I–V and P–V characteristics of all five PV circuit models under constant temperature and irradiance, as mentioned in the datasheet of the reference panel KC200GT have been generated for analysis. When the inbuilt MATLAB solar cell block was simulated, the characteristics obtained are not conforming to ideal. The second simulation is carried out using the inbuilt PV array block available in MATLAB. The electrical characteristics obtained in this case are good but there is limitation of the inability to change the parameters as required. The model proposed by Mohan and Dhinakaran gives the desired output characteristics but it is not simple and it requires more time for implementation than other models. The model proposed by M.G. Villalva also gives the required electrical characteristic. It is easy and simple to implement but the model development procedure steps are not clear. Nguyen and Nguyen have proposed step by step procedure for modeling of PV panel. The comparative analysis of selected models of PV panel are shown in Table 3.

The proposed model has been developed using Villalva's mathematical equations and steps proposed by Nguyen. It not only gives the desired output characteristics but can be implemented in less time and is easy to develop in a manner suitable for varying the parameters and model specifications. The effect of recombination phenomena was also included by use of two diode model in the next step.

This model is also applicable for the study of effect of variation in environment conditions such as varying temperature, irradiation, and especially partial shadow effect. A comparative analysis of these five different simulations models of PV panel have been carried out successfully. It is expected that this comparative analysis will be useful for designing accurate models for research purposes. It is also expected to be useful for accurate prediction of the PV system output for better planning and management of distributed generation to improve the performance and efficiency of this energy sector.

ACKNOWLEDGMENTS

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

REFERENCES

1. Nituca, C., Chiriac, G., Cuciureanu, D., Zhang, G., Han, D., and Plesca, A., Numerical analysis of a real photovoltaic module with various parameters, *Hindawi Model. Simul. Eng.,* 2018, vol. 2018, p. 7329014. https://doi.org/10.1155/2018/7329014
2. Surya Kumari, J. and Sai Babu, Ch., Mathematical modeling and simulation of photovoltaic cell using Matlab-Simulink environment, *Int. J. Electr. Comput. Eng. (IJECE),* 2012, vol. 2, no. 1, pp. 26–34. ISSN: 2088-8708.
3. Krismadinata, Rahim, N.A., Ping, H.W., and Selvaraj, J., Photovoltaic module modeling using Simulink/Matlab, *3rd Int. Conf. on Sustainable Future for*

Human Security SUSTAIN 2012, 2013, vol. 17, pp. 537–546.
https://doi.org/10.1016/j.proenv.2013.02.069

4. Bouraiou, A., Hamouda, M., Chaker, A., Sadok, M., Mostefaoui, M., and Lachtar, S., Modeling and simulation of photovoltaic module and array-based on one and two diode model using MATLAB/Simulink, *Int. Conf. on Technologies and Materials for Renewable Energy, Environment and Sustainability, TMREES15, Energy Procedia,* 2015, vol. 74, pp. 864–877.
5. Mahmodian, M.S., Rahmani, R., Taslimi, E., and Mekhilef, S., Step by step analyzing, modeling and simulation of single and double array PV system in different environmental variability, *Int. Conf. on Future Environment and Energy IPCBEE,* 2012, vol. 28, pp. 37–42.
6. Bellia, H., Youcef, R., and Fatima, M., A detailed modeling of photovoltaic module using MATLAB, *NRIAG J. Astron. Geophys.,* 2014, vol. 3, pp. 53–61.
7. Mohan, K. and Dhinakaran, R., Modeling and simulation of solar PV cell with MATLAB/Simulink and its experimental verification, *J. Innov. Res. Solutions (JIRAS),* 2014, vol. 1, no. 1, pp. 118–124.
8. Villalva, M.G., Gazoli, J.R., and Filho, E.R., Modeling and circuit-based simulation of photovoltaic arrays, *Braz. J. Power Electron.,* 2009, vol. 14, no. 1, pp. 35–45.
9. Nguyen, X.H. and Nguyen, M.P., Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink, *Environ. Syst. Res.,* 2015, vol. 4, p. 24.
https://doi.org/10.1186/s40068-015-0047-9
10. AbdelHady, R., Modeling and simulation of a micro grid-connected solar PV system, *Water Sci.,* 2017, vol. 31, pp. 1–10.
https://doi.org/10.1016/j.wsj.2017.04.001
11. Veerachary, M., PSIM circuit-oriented simulator model for the nonlinear photovoltaic sources, *IEEE Transactions on Aerospace and Electronic Systems,* 2006, vol. 42, no. 2, pp. 735–740.
12. Ahmad, G.E., Hussein, H.M.S., and El-Ghetany, H.H., Theoretical analysis and experimental verification of PV modules, *Renewable Energy,* 2003, vol. 28, pp. 1159–1168.
13. Agrawal, N., et al., Performance enhancement by novel hybrid PV array without and with by-pass diode under partial shaded conditions: an experimental study, *Int. J. Renewable Energy Res.,* 2021, vol. 11, no. 4, pp. 1880–1891.