

Bana, Sangram; Saini, R. P.

Article

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A mathematical modeling framework to evaluate the performance of single diode and double diode based SPV systems



Sangram Bana^{*}, R.P. Saini

Alternate Hydro Energy Centre, Indian Institute of Technology, Roorkee 247667, India

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ABSTRACT

In order to predict the performance of a PV system, a reliable and accurate simulation design of PV systems before being installed is a necessity. The present study concerns the development of single and double diode model of solar PV system and ensures the best suited model under specific environmental condition for accurate performance prediction. The information provided in the manufacturers' data sheet is not sufficient for developing a Simulink based single and double diode models of PV module. These parameters are crucial to predict accurate performance of a PV module. These parameters of the proposed solar PV models have been calculated using an efficient iterative technique. This paper compares the simulation results of both the models with manufacturer's data sheet to investigate the accuracy and validity. A MATLAB/Simulink based comparative performance analysis of these models under inconsistent atmospheric conditions and the effect of variations in model parameters has been carried out. Despite the simplicity, these models are highly sensitive and respond to a slight variation in temperature and insolation. It is observed that double diode PV model is more accurate under low intensity insolation or shading condition. The performance evaluation of the models under present study will be helpful to understand the I-V curves, which will enable us in predicting the solar PV system power production under variable input conditions.

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1. Introduction

Solar PV systems are environmentally friendly and assist in minimizing GHG emissions that would have otherwise arisen due to the use of fossil fuels for power generation. Feeding electricity into the grid by solar PV plants can help in to transmit equal amounts of electricity as would have been generated from the GHG intensive grid (most power grids receive electricity from coal based power plants). However, the high cost of photovoltaic power system modules inhibits optimum and utmost utilization of available solar energy. Thus, before actually installing the system, it is necessary that reliability and accuracy of the system is ensured in simulated environments.

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A PV system converts light into electricity. More precisely, a PV cell converts incoming solar radiation into direct current (DC). A PV cell is the heart of the solar power system, and sunlight being free of cost and available in abundance, can be used as an alternative energy source. The word “photovoltaic” originates from the word “light” pronounced as “photo” in Greek, and “voltaic” from Alessandro Volta—an electricity pioneer. The ability of photovoltaic material to convert light energy into electrical energy was discovered by Edmond Becquerel—a French physicist, in 1839. Although the use of sunlight to produce electric current in solid materials was also recognized by Becquerel, it took a century to understand this procedure of conversion. Nonetheless, scientists have identified materials that exhibit photovoltaic properties of converting light energy into electrical energy at the atomic level (Tossa et al., 2014; Alsayid, 2012). A number of solar cells are attached in series or parallel (depending upon the necessity) in a single support system known as a “PV module”. Depending

^{*} Corresponding author. Fax: +91 1332 286125.

E-mail address: sonamdah@iitr.ac.in (S. Bana).

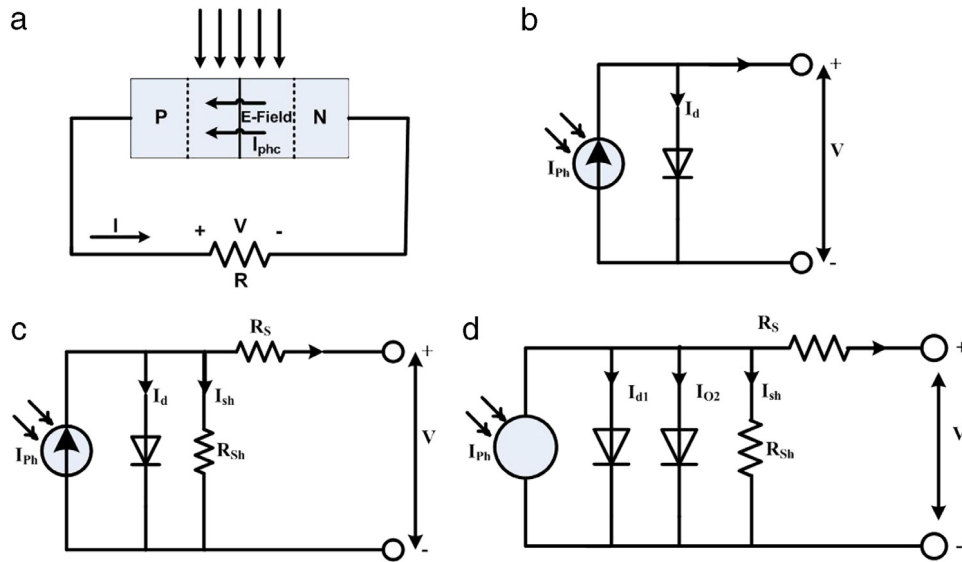


Fig. 1. Solar PV cell and its equivalent electrical circuits: (a) SPV Cell; (b) Ideal model; (c) single diode model; (d) double diode model.

upon the requirement of current and voltage combinations, these modules can further be connected in series or parallel arrangements known as “array” of PV modules (Anne and Michel, 2006; Bourdouden and Gastli, 2007).

Performance of solar PV cell is evaluated under standard test conditions i.e. cell temperature at 25 °C; insolation of 1000 W/m²; and solar spectrum at A.M 1.5. Thus, it is important to accurately predict the power output of PV module under real weather conditions before installing solar PV systems. Various solar PV models have been proposed by researchers and each model comes with certain advantages of its own (Phang et al., 1984; Townsend, 1989; Glass, 1996; Dongue et al., 2012; Karamirad et al., 2013). Townsend (Townsend, 1989). Further, researchers in the past have considered constant parameters (ideality factor, series and shunt resistance) for solar PV cell modeling. Results thus obtained were inaccurate as these parameters vary with change in temperature and insolation. Various studies have been carried out on the model development of the PV modules. However the modeling of these models has different level of complexity of their own. These models may be differentiated on the basis of number of employed diodes, finite or infinite shunt resistance, fixed or variable ideality factor and the techniques used to determine the unknown parameters (Saloux et al., 2011; Lun et al., 2013; Kulaksiz, 2013; Siddiqui and Abido, 2013; Ma et al., 2014). The result of comparative studies does not provide that “which model will provide better results under real environmental exposure conditions and which model should be considered to study the effect of shading and non-shading conditions?”

The present study is a comparative study of single diode and double diode solar PV models. Development of these models is done by evaluating their respective equivalent circuits. The performance characteristic of PV components is estimated on the basis of electrical parameters of the equivalent circuits. The effect of variation in environmental factors (insolation and temperature) and internal parameters (ideality factor and series resistance) on both models has been evaluated and extensively discussed in this study. This performance assessment will help in understanding $I-V$ curves for forecasting PV system output power under inconsistent input conditions. Parameters such as ideality factor (n), series resistance (R_s) and shunt resistance (R_{sh}) are unfortunately not provided in manufacturer data sheets. (These parameters are termed as unknown parameters.) These unknown parameters have been determined by an iterative method. This

study evaluates the performance of presented SPV models under variable operating conditions and analyzes their power deviation with respect to the ideal solar PV model.

The modeling process is divided into three parts: First, mathematical modeling of single and double diode models and unknown parameters are determined. Second, simulation models of these solar PV models in Matlab/Simulink environment are presented. Finally, the accuracy of the proposed models is validated by comparing simulation results against manufacturer data sheets.

The experimental data is measured at National institute of Solar Energy (NISE), Gawalpahari, Gurgaon-Faridabad road, Haryana, India. This data has been considered for comparing $I-V$ curves of the proposed models with the measured $I-V$ curves obtained under controlled operating conditions in this study (latitude = 28.4700°N and longitude = 77.0300°E). A commercial PV module MSX60 (Polycrystalline silicon), manufactured by Solarex has been considered as reference module for this study.

2. Simulation models of solar PV device

In order to determine the electrical characteristics of solar photovoltaic cell accurately, mathematical modeling of single and double diode models is presented in the following subsections.

2.1. Solar PV cells, modules and arrays

A cell is a fundamental unit of PV system. A group of cells are encapsulated to form a module. In order to increase the voltage level, modules are connected in series and to increase current levels, modules are connected in parallel depending on load requirements.

2.2. Equivalent circuits of solar PV device and their mathematical models

A solar PV cell is conventionally represented by an equivalent circuit comprising a current source and one or two forward biased diodes without the correlation of internal series resistance and shunt resistance in case of an ideal cell, and with internal series resistance (R_s) and shunt resistance (R_{sh}) in case of single diode and double diode models. The equivalent circuits of an ideal cell, a single diode and a double diode SPV cell model are represented in Fig. 1 (Tossa et al., 2014; Patel and Agarwal, 2008; Villalva et al.,

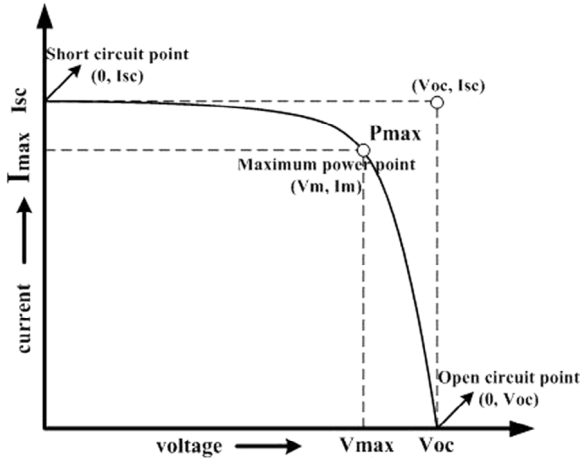


Fig. 2. I - V characteristics curve of a PV cell.

2009; Rauschenbach, 1980; Jain and Kapoor, 2004). These models exhibit voltage and current data as output. These data outputs provide the I - V characteristic curve as shown in Fig. 2.

2.3. Modeling of solar PV system

Modeling of solar PV cell can be achieved by extensively analyzing the mathematical equations based on the respective equivalent circuits of solar PV models presented in following subsections (Bellia et al., 2014; Benlarbi et al., 2004; Gow and Manning, 1999; Hadj Arab et al., 2004; Sera et al., 2007).

2.3.1. Ideal PV cell modeling

Ideal solar PV cell is represented by photo-generated current I_{phc} , which diverges from ideal outcome due to electrical and optical losses. The ideal PV cell model presented in Fig. 1(b) is the simplest PV model as the effect of series and parallel resistance are not considered. Output current of the cell is represented by I - V characteristics and mathematically expressed as:

$$I = I_{phc} - I_d. \quad (1)$$

The diode current I_d , signifies diffusion and recombination currents in quasi steady state regions of emitter and excess concentration regions of PN junction. This diode current is represented by Shockley equation as:

$$I_d = I_s \{ e^{V_d/nV_T} - 1 \} \quad (2)$$

where ' V_d ' is the diode Voltage, V_T is termed as thermal voltage ($V_T = kT/q$) due to its substantial temperature dependence, q is the charge of an electron ($= 1.6 \times 10^{-19}$ C), n is the ideality factor (1.7), K is the Boltzmann constant ($= 1.3805 \times 10^{-23}$ J/K) and T is the cell temperature (K) (Anne and Michel, 2006; Sheik Mohammed, 2011).

$$I = I_{phc} - I_s (e^{qV_d/nKT} - 1). \quad (3)$$

Ideal solar PV cell does not consider the effects of internal resistance, thus fails to establish an accurate relationship between cell current and voltage.

2.3.2. Single diode PV cell modeling

Generally, a series resistance (R_s), is introduced to the ideal cell model in order to get precise results. Although this model is simple, it reveals deficiencies when subjected to temperature variations. This model has been extended by considering a shunt resistance (R_{sh}). This single diode or five parameter model consists

of current producer and diode with series and shunt resistances as shown in Fig. 2(c). The series resistance represents the resistance (ohmic loss) offered to the current flow due to ohmic contact (metal-semiconductor contact) and resistance due to impurity concentrations along with junction depth. Leakage current across the junction signifies shunt resistance, R_{sh} , connected parallel to the diode. The mathematical representation of the output current in Eq. (1) is modified as:

$$I = I_{phc} - I_d - V_d/R_{sh} \quad (4)$$

where V_d , is the diode voltage which is represented as:

$$V_d = V + IR_s \quad (5)$$

where V , is the input voltage and I , is the current output. It is recognized that I - V characteristic curve of a PV device is affected by series and shunt resistance, output voltage is affected by series resistance, and shunt resistance is responsible for reduction in available current (Jain and Kapoor, 2004; Tsai et al., 2008). Eq. (3) is further modified to obtain the single diode model equation. The single diode model of SPV cell is represented as:

$$I = I_{phc} - I_s \left\{ e^{qV_d/nKT} - 1 \right\} - \frac{V + IR_s}{R_{sh}}. \quad (6)$$

2.3.3. Double diode PV cell modeling

Although the single diode model carries some improvement, yet its accuracy is questionable. To overcome this problem, a two diode model is introduced considering two diodes connected in parallel to the current source, shown in Fig. 1(d). The current I_{d1} , through the first diode is the current component same as I_d in case of single diode model. The current through the second diode I_{d2} , is the recombination current in space charge region. This suggests that two Shockley terms contribute to the saturation currents of a solar PV cell. Series resistance R_s , and shunt resistance R_{sh} , are same as defined for single diode model. The double diode model of a SPV cell is highly accurate at low insolation levels. The double diode model can be represented by the following equation (Ma et al., 2014; Tsai et al., 2008; Ishaque and Salam, 2011):

$$I = I_{phc} - I_{s1} \left\{ e^{qV_d/n_1KT} - 1 \right\} - I_{s2} \left\{ e^{qV_d/n_2KT} - 1 \right\} - \frac{V + IR_s}{R_{sh}} \quad (7)$$

where I_{s1} and I_{s2} are saturation currents of corresponding diodes.

2.3.4. Other equations involved in PV cell modeling

The dependency of saturation current (I_s) and photo generated current (I_{phc}) in a PV cell on temperature and insolation is shown by the following equations:

- (i) Saturation current of a solar PV cell varies with the cubic function of temperature shown in Fig. 3, which is represented by the following equation:

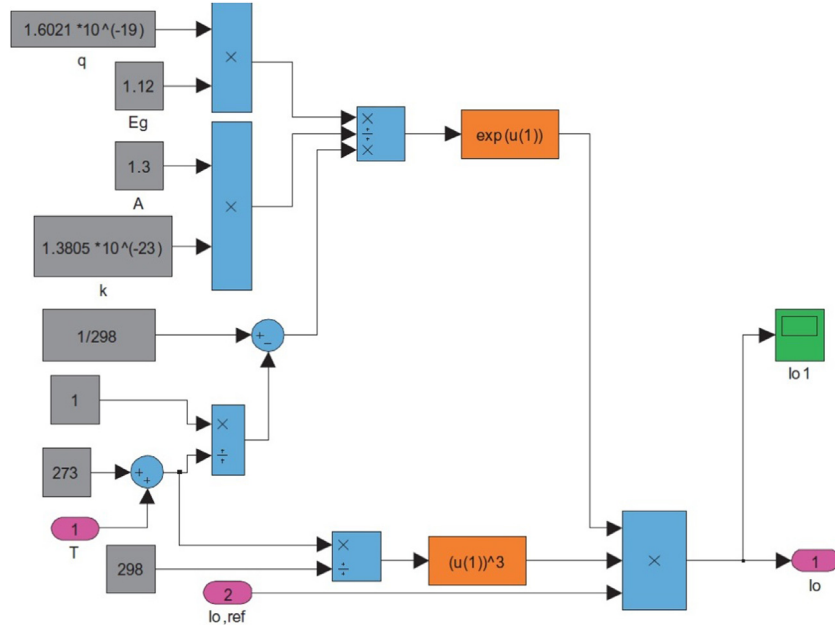
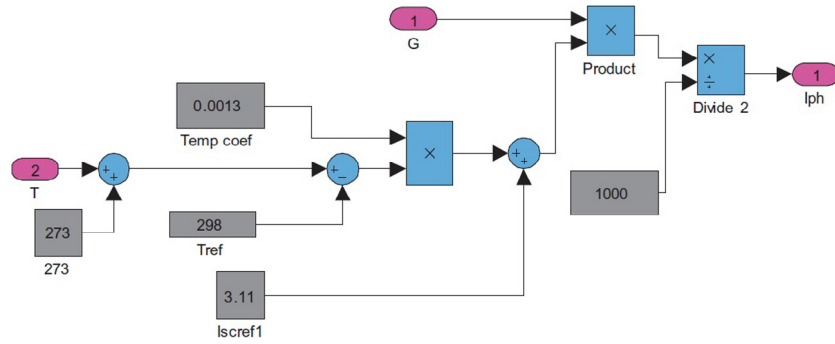
$$I_s = I_{rs} (T/T_r)^3 e^{\left[\frac{qE_{bg}}{nk} \{ 1/T_r - 1/T \} \right]} \quad (8)$$

where I_{rs} , T_r , and E_{bg} are reverse saturation current, ambient temperature and energy band gap (1.1 eV) respectively.

- (ii) Reverse saturation current at a reference temperature T , can be given by the following equation:

$$I_{rs} = I_{sc} / e^{(qV_{oc}/nkT)} - 1 \quad (9)$$

where I_{sc} , V_{oc} are short circuit current and open circuit voltage. The saturation current depends on current density and effective area of the cell. The intrinsic characteristic determines current density.

Fig. 3. Detailed I_s implementation.Fig. 4. Detailed I_{ph} implementation.

(iii) Photo generated current shares a linear relationship with insolation and depends on temperature (see Fig. 4). It is represented by the following equation:

$$I_{phc} = \{I_{sc} + K_i (T - T_r)\} \frac{H_T}{1000} \quad (10)$$

where K_i is temperature coefficient of cell's short circuit current and H_T is the insolation on the solar cell. I_{phc} , I_s , n , R_s , and R_{sh} are five unknown parameters for single diode model and I_{phc} , I_{s1} , I_{s2} , n_1 , n_2 , R_s , and R_{sh} are seven unknown parameters for double diode model of solar PV cell. The photocurrent generated by incident solar radiation varies with change in temperature and solar radiation. By determining the above parameters, modeling of solar PV arrays can be achieved. Table 1 represents the series/parallel connected modules (Jain and Kapoor, 2004; Ishaque, 2011; Chouder et al., 2012). This series-parallel topology is represented by Fig. 5.

Based on Fig. 5, the output current for series-parallel configuration for single diode and double diode model can be written as:

$$I = N_p \left\{ I_{phc} - I_{s1} \left[\exp \left(\frac{V + I R_s \left(\frac{N_s}{N_p} \right)}{V_{T1} N_s} \right) - 1 \right] - \frac{V + I R_s \left(\frac{N_s}{N_p} \right)}{R_{sh} \left(\frac{N_s}{N_p} \right)} \right\} \quad (11)$$

$$I = N_p \left\{ I_{phc} - I_{s1} \left[\exp \left(\frac{V + I R_s \left(\frac{N_s}{N_p} \right)}{V_{T1} N_s} \right) - 1 \right] - I_{s2} \left[\exp \left(\frac{V + I R_s \left(\frac{N_s}{N_p} \right)}{V_{T2} N_s} \right) - 1 \right] - \frac{V + I R_s \left(\frac{N_s}{N_p} \right)}{R_p \left(\frac{N_s}{N_p} \right)} \right\} \quad (12)$$

where V_T is the thermal voltage ($V_T = nkT/q$, $V_{T1} = n_1 kT/q$ and $V_{T2} = n_2 kT/q$). In order to increase voltage levels, the number of modules is to be connected in series while to increase current levels, they are connected in parallel depending on the load requirements.

3. Determination of model parameters

Greater accuracy can be achieved by computing the unknown parameters, namely I_{pv} , I_{s1} , (I_{s2} in case of two diode model), R_p , R_{sh} , n_1 and (n_2 in case of two diode model). The photo generated current as a function of insolation and temperature is represented by Eq. (10). The saturation current for a single diode model considering temperature variation is given in Eq. (16). In case of double diode model, several researchers (Ishaque, 2011; Ishaque and Salam, 2011; Sheik Mohammed, 2011; Kulaksiz, 2013) have

Table 1
Transformed parameters for series and parallel connected modules.

Parameters of SPV cell	Parameters of series arrays of N_s cells	Parameters of parallel arrays of N_p cells
I_{phc}	I_{phc}	$N_p I_{phc}$
I_{rsc}	I_{rsc}	$N_p I_{rsc}$
V_t	$N_s V_t$	V_t
R_s	$N_s R_s$	R_s / N_p
R_{sh}	$N_s R_{sh}$	R_{sh} / N_p

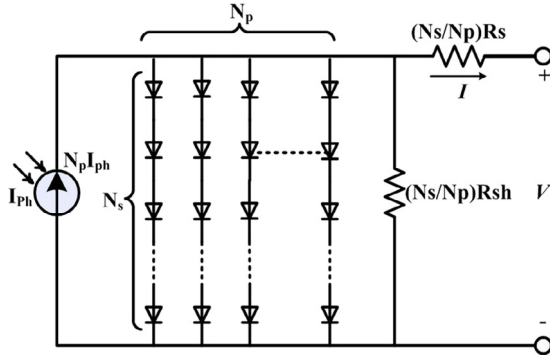


Fig. 5. Equivalent circuit model of PV array.

computed the values of I_{s1} and I_{s2} through iterative techniques. These techniques are responsible for increase in computation time and complexity. Therefore, both saturation currents were derived analytically, and can be determined by Eq. (17).

$$I_s = \frac{[I_{pv} + K_i (T - T_r)]}{\exp[(V_{oc} + K_v (T - T_r)) / n V_T] - 1} \quad (13)$$

$$I_{s1} = I_{s2} = I_s = \frac{[I_{pv} + K_i (T - T_r)]}{\exp[(V_{oc} + K_v (T - T_r)) / \{(n_1 + n_2) / p\} V_T] - 1}. \quad (14)$$

As computation turns out to be easy due to equalization, iterations are eliminated and an analytical solution is obtained. According to Shockley's theory of diffusion, ideality factor n_1 must be unity. Ideality factor n_2 should be less than or equal to 1.2 as determined through simulation. This estimation provides the best match between the I - V curves of practical model and proposed models. As $(n_1 + n_2) / p = 1$ and $n_1 = 1$, it shows that variable p is preferred to be less than or equal to 2.2. This uncertainty in determining the values of n_1 and n_2 can be eliminated and Eq. (7) is re-arranged in terms of p as shown by Eq. (18).

$$I = I_{phc} - I_{s1} \{e^{qV_d/KT} - 1\} - I_{s2} \{e^{qV_d/(P-1)KT} - 1\} - \frac{V + IR_s}{R_{sh}}. \quad (15)$$

The expression for R_{sh} at P_{max} can be arranged as follows:

$$R_{sh} = \frac{V_{mp} + I_{mp} R_s}{[I_{phc} - I_o \left\{ \exp\left(\frac{V_{mp} + I_{mp} R_s}{V_T}\right) + \exp\left(\frac{V_{mp} + I_{mp} R_s}{(p-1)V_T}\right) - 2 \right\} - \frac{P_{max, E}}{V_{mp}}]}. \quad (16)$$

Considering a simple iterative method, the value of R_s is iteratively increased while R_{sh} is calculated simultaneously. For initializing the iteration process, the appropriate values of R_{sh} and R_s are considered (Lun et al., 2013). Value of R_s is taken as zero and the value of R_{sh} is obtained using the following equation:

$$R_{sh0} = \left(\frac{V_{mp}}{I_{sc} - I_{mp}} \right) - \left(\frac{V_{oc} - V_{mp}}{I_{mp}} \right). \quad (17)$$

The proposed SPV Simulink models represent a generalized SPV model. The input parameters for both models are insolation and temperature while I - V and P - V characteristics are obtained

as output parameters under different input conditions. The characteristic curves of both models are exhibited by highly non-linear radiation and temperature which are being simulated for the parameters given in Table 1.

4. Basic parameters

- Short-circuit current:** In case of electrodes of the SPV cell is short-circuited, the current that flows through the circuit is termed short-circuit current (I_{sc}). It is the maximum current that flows through the SPV cell. The short-circuit current of a solar cell depends on the insolation incident on SPV cell, which is determined by the spectrum of the incident light, i.e. AM 1.5 spectrum. I_{sc} depends on the cell area and its ability to absorb incident solar radiation (Bourdoucen and Gastli, 2007).
- Open circuit voltage:** It is the maximum voltage that can be delivered by a cell. The V_{oc} corresponds to the forward bias voltage, at which the dark current compensates the photo-current. The V_{oc} depends on photo-generated current density and can be expressed as:

$$V_{oc} = \frac{n * K * T}{q} \ln \frac{I_{pv}}{I_0}; \quad I_{pv} > I_s. \quad (18)$$
- Maximum voltage (V_{mp}) and current (I_{mp}):** It is the power at a point on I - V curve, the product of maximum current and voltage is the maximum power point.
- Temperature:** Solar cells work best at low temperature as determined by their material properties. As the temperature exceeds operating temperature, cell efficiency decreases. A substantial part of the incident insolation is lost in the form of heat resulting in high temperature of cells.
- Resistance:** Large electrical contacts can minimize electrical resistance, but covering a cell with large, opaque metallic contact would block too much incident light. Therefore, a tradeoff must be made between loss due to resistance and loss due to shading effects (Chan and Phang, 1987a,b).
- Standard test condition (STC):** The standard test conditions for a cell are specified as follows: solar radiation—1000 W/m², cell temperature—25 °C and spectral distribution—AM 1.5.
- Incoming solar radiation:** In order to analyze the proposed model, the input solar radiation data considered to perform the experiment is measured at National Institute of Solar Energy (NISE), Gurgaon (a city in Haryana, India). The considered solar radiation (total solar radiation considering beam, diffused and reflected solar radiation incident on the surface of a PV module), module temperature and ambient temperature along with date and time under the present study are given in Table 4.

Developers and engineers also require an accurate model to evaluate the energy yield of the PV system. However, the information provided by the manufacturers is not enough to determine the energy yield of the PV power system. Also the specifications provided by the manufacturer are under STC. To make these specifications effective under other environmental conditions an accurate and reliable PV model is needed inevitably.

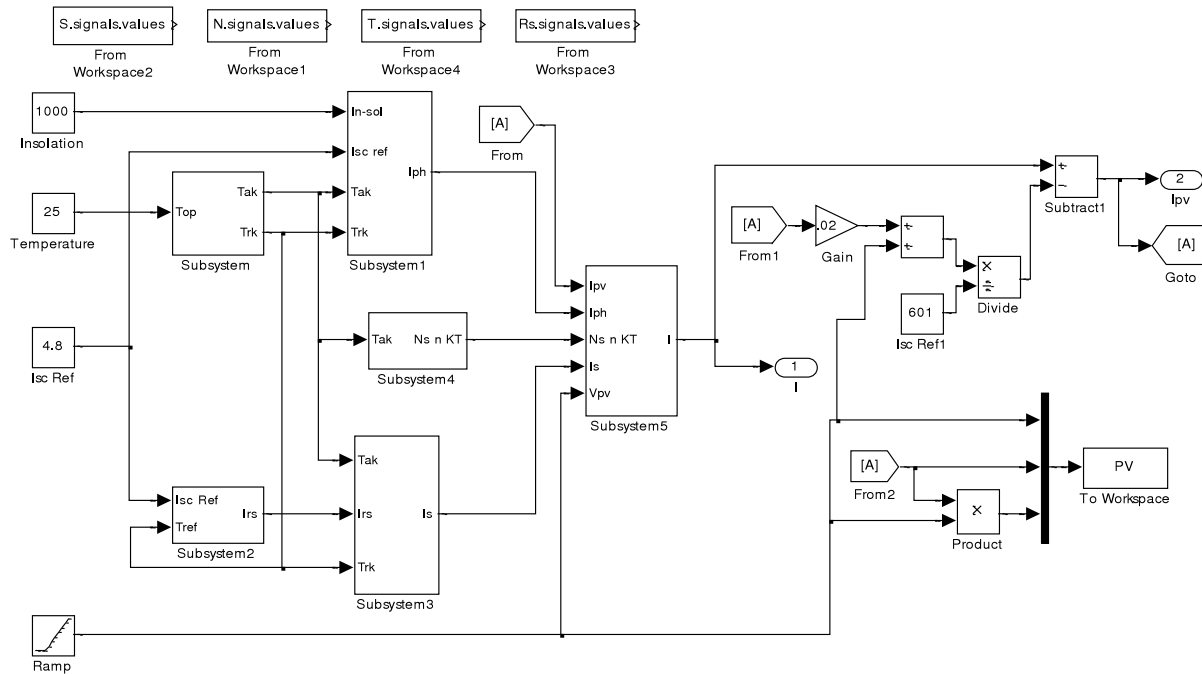


Fig. 6. Simulink model of single diode SPV system model.

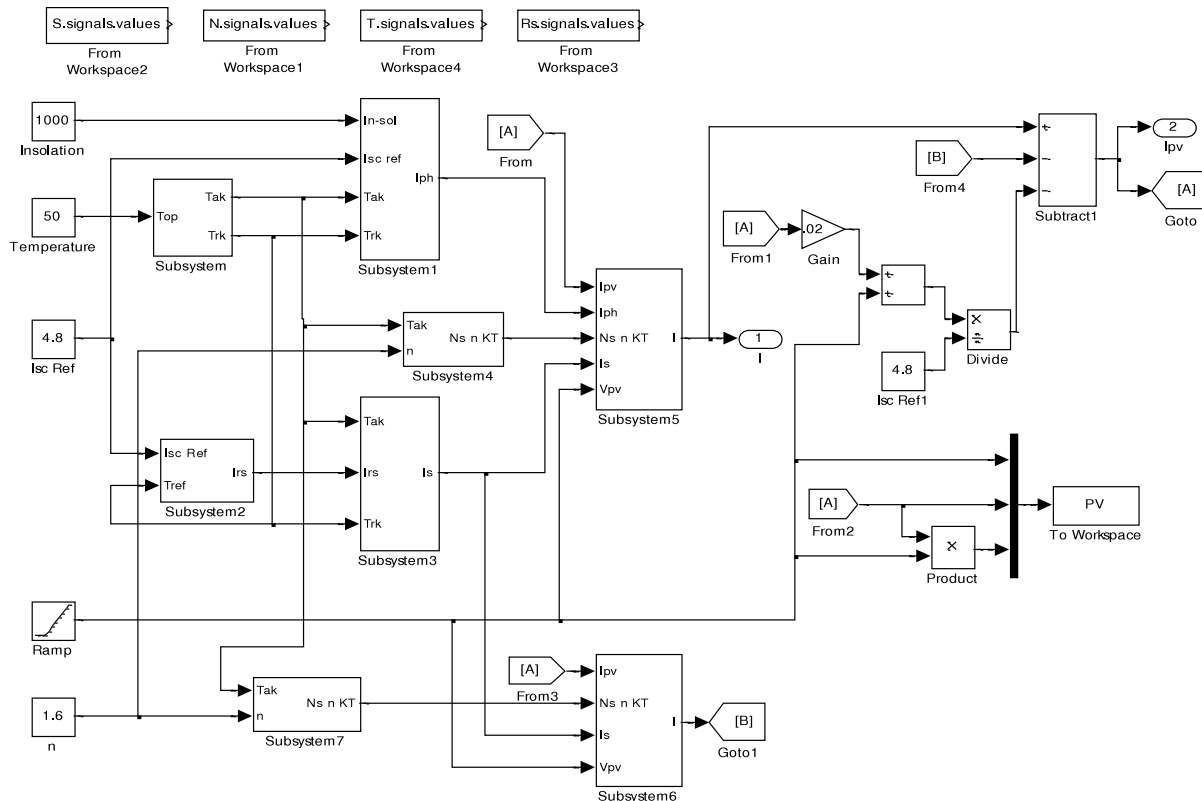


Fig. 7. Simulink model of two diode SPV system model.

5. Modeling of single diode SPV model

This study offers a simple, reliable and accurate model with a current source, series resistance, parallel correlation of forward biased diode and shunt resistance, and is presented in Fig. 6 using the mathematical equations discussed in Section 2. The output current (I) of an ideal diode is represented in subsystem 5 (excluding subsystems 2 and 3). Here, subsystem 1 determines

the photo-generated current (I_{phc}), subsystem 3 determines the reverse saturation current and subsystem 2 determines the temperature dependency of reverse saturation current. Values of R_s and R_{sh} are calculated through iterations. After finding the values of R_s and R_{sh} , I_s and n can be calculated easily. Modeling of single diode model provides values of current, voltage and power as output in workspace of MATLAB.

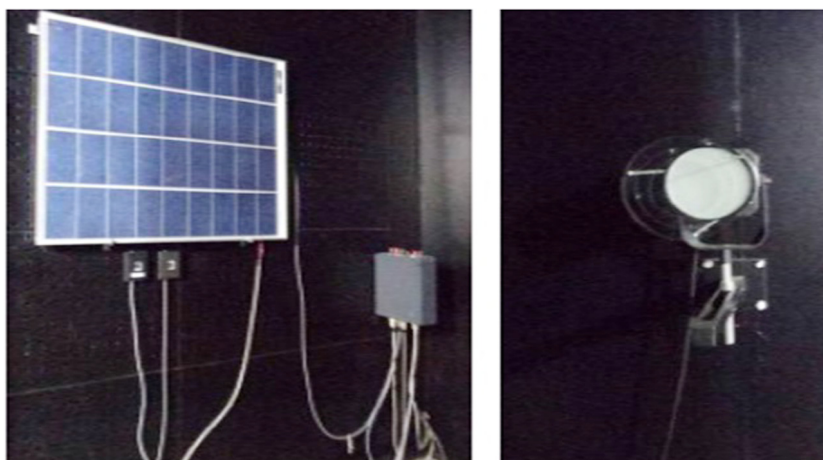


Fig. 8. ENDEAS QUICKSUN 700A solar simulator.

Table 2

Key specifications of Solarex MSX 60 (Polycrystalline silicon) PV module.

COMPANY : Solarex MODEL: MSX 60	
Parameters	Values
Peak power (P_{max}) (W)	60
Max peak voltage (V)	17.1
Max peak current (A)	3.5
Open circuit voltage (V)	21.1
Short circuit current (A)	3.8
K_v (V/°C)	-80×10^{-3}
K_i (A/°C)	3×10^{-3}
N_p	1
N_s	36

Table 3

Estimated parameters of Solarex MSX-60 (Polycrystalline silicon) PV module.

Solarex MSX-60	
Parameters	Calculated by Newton method
I_{ph} (A)	3.8084
I_{s1} (I_s) (A)	4.8723
I_{s2} (A)	6.1528
R_s	0.3692
R_{sh}	169.0471
n_1 (n)	1.0003
n_2	1.9997

6. Modeling of two diode SPV model

Following a procedure similar to that of single diode modeling which has been discussed earlier, modeling of two diode solar PV model along with R_s and R_{sh} is accomplished. The first diode represents charge diffusion in quasi steady state along with recombination current in high concentration region of PN junction and the second diode considered here represents recombination current in space charge region. The two diodes connected in parallel to the current source are represented by subsystems 5 and 6 as shown in Fig. 7. The current outputs I_{d1} and I_{d2} are calculated accordingly. Values of current, voltage and power are obtained as output in workspace of MATLAB.

7. Results and discussions

The present study presents and analyzes modeling of single and double diode models of solar PV module. These models are obtained by implementing equations in MATLAB/Simulink

environment based on their respective equivalent circuits as discussed in Section 2.

7.1. Model verification

The outdoor measurement for poly-crystalline technology based PV module was carried out at National institute of Solar Energy (NISE), 19th milestone Gawalphari, Gurgaon-Faridabad Road, Haryana (India). This site has specific composite climate type environment distinguished by high insolation and temperature levels. The geographical location of NISE is: latitude 28.4700°N and longitude 77.0300°E with an elevation of 216 m from sea level.

In order to carry out measurements of I - V and P - V under STC in accordance with manufacturer data sheet, a calibrated ENDEAS QUICKSUN 700A solar simulator shown in Fig. 8 has been used. The main parameters such as I_{sc} , V_{oc} , I_{mp} , V_{mp} and P_{mp} at STC are obtained according to International Standards for Crystalline silicon modules (IEC 61215 Ed. 2 - 2005, Xiao et al., 2004).

A commercial PV module MSX 60 (Polycrystalline silicon), manufactured by Solarex has been considered as reference module to investigate the effect of varying insolation, temperature, ideality factor, series and shunt resistance on the output of both the Simulink models for this study. The key specifications of Solarex MSX 60 module as provided by the manufacturer are presented in Table 2 (<http://www.solarelectricsupply.com/media/custom/upload/Solarex-MSX64.pdf>). Table 3 shows the computed unknown parameters discussed in Section 4.

Although two diode solar PV model has more unknown parameters, the specific unknown parameters to be determined are four since $I_{s1} = I_{s2}$ whereas n_1 and n_2 can be randomly chosen from Eq. (3).

Further, the unknown parameters determined by numerical iteration method (Table 3) are compared with the data sheet at STC (Table 2) for both the models. Fig. 9a, 9b shows an excellent match between manufacturer curves and computed results at STC. Fig. 9a shows computed curves of MSX-60 module for single and double diode models, and the curves are compared with manufacturer data sheets at different insolation and constant temperature ($=25^\circ\text{C}$). Fig. 9b shows computed curves of MSX-60 module for single and double diode models as compared with manufacturer data sheets at different temperatures and constant insolation (1000 W/m^2). From these figures, the inaccuracies and inefficiencies of single diode model as compared with two diode model at different irradiances and temperatures can be observed. Fig. 9a indicates a good agreement between provided and calculated data at different irradiances especially at low irradiance in case of two diode model or seven parameter model.

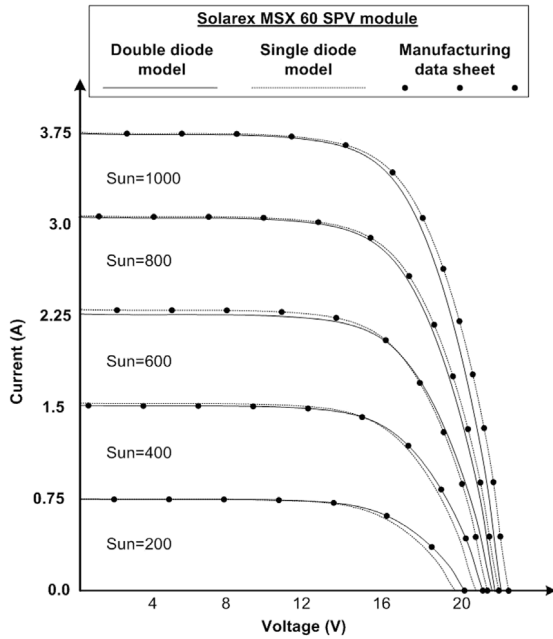


Fig. 9a. I - V curves of single and double-diode model of the Solarex MSX 60 SPV module for several irradiation levels.

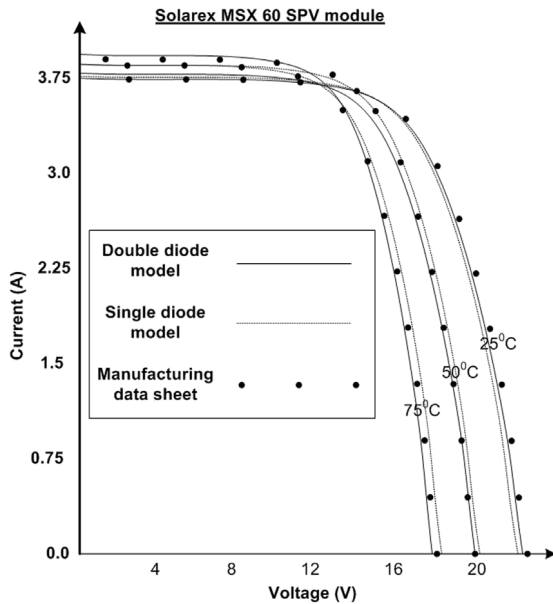


Fig. 9b. I - V curves of single and double-diode model of the Solarex MSX 60 SPV module for several temperature levels.

From Fig. 9a it can be observed that single diode PV model provides accurate results for high solar insolation whereas double diode PV model is more accurate under low intensity insolation or shading condition.

7.2. Model verification under real operating conditions:

The measurements of the I - V and P - V characteristic curve of the considered technology module were performed with data acquisition system PVPM-2540 C, Solar radiation sensor SOZ-03, Personal computer—hp 4th generation Intel i-3 processor as shown in Fig. 10. PVPM device measures the I - V curves of PV modules. It also measures and calculates the peak power at the place of installed PV system. Peak power is the power measured under STC.

As mentioned previously, in order to validate both the Simulation models for PV module, the characteristic I - V curves of the considered module was determined under real operating conditions and compared with the computed simulated curves presented. The result thus obtained is presented in Table 4. Using the identified parameters presented in Table 5, the characteristic I - V and P - V curves for the selected module was computed under real operating conditions and are demonstrated in Fig. 11 along with the simulated I - V curves.

7.3. Simulation results:

For easy implementation, the solar radiation intensity for a sample day is anticipated to be a function of Gaussian function distribution expressed as (Messenger and Ventre, 2000)

$$\lambda(t) = \lambda_{\max} \exp \left[-\frac{(t - t_c)^2}{2\sigma^2} \right]$$

where λ_{\max} is the utmost sunlight intensity at a particular time, t_c is the center time, and σ is the standard deviation of Gaussian function. Fig. 12 illustrates a plot of the Gaussian function distribution for the solar radiation intensity for a sample day with the conditions: $\lambda_{\max} = 1 \text{ kW/m}^2$, $t_c = 12$, and $\sigma = 0.5$.

The peak of sunlight intensity occurs at noon. In addition, the ambient temperature for such a sample day is assumed to be a Gaussian function distribution. For deviations in solar irradiance and ambient temperature, the cell temperature can be predicted by Eq. (9). Both ambient and cell temperature are also presented in Fig. 12. For an insolation-oriented model of PV module, the cell temperature is affected by sunlight irradiance. For different output voltage, the output current and power are obtained in Figs. 13a and 13b for a sample day.

The insolation values specified above and temperature value of 25°C are taken as inputs for the proposed models. The output of single and double diode SPV models is given in Table 6.

Based on the output of single and double diode SPV models, the I - V characteristic curves for these models are obtained as shown in Fig. 14. This figure illustrates that the power output of both single and two diode SPV models is same up to a voltage of 7.03 V ($P_{\text{single}} = P_{\text{double}} = 26.64 \text{ W}$). Beyond this voltage, power output of double diode SPV model starts decreasing as compared to single diode SPV model ($P_{\text{double}} = 37.70 \text{ W}$ and $P_{\text{single}} = 37.80 \text{ W}$) due to decrease ingenerated current ($I_{\text{double}} = 3.77 \text{ A}$, $I_{\text{single}} = 3.78 \text{ A}$ at $V = 10 \text{ V}$). This variation in power output of double diode SPV model may be due to consideration of recombination losses in space charge region represented by subsystem 6 in Fig. 7. These Recombination losses effect both the current collection (therefore the short-circuit current) as well as the forward bias injection current (and therefore the open-circuit voltage). The decrease in current of double diode SPV model is continuous. The value of current is nearly zero at 19.81 V for double diode SPV model and in case of single diode SPV model the value of current is approximately zero at 21.07 V . Therefore, it is observed that both short circuit current and open circuit voltage is affected by consideration of second diode in case of double diode SPV model as compared to single diode SPV model under specified operating conditions.

The effect of environmental factors such as insolation level, temperature (provided as inputs from Matlab workspace) and effect of internal parameters such as ideality factor, series and shunt resistance are analyzed in this study to match the parameters (I_{sc} , V_{oc} , I_{mp} , V_{mp} , P_{max}) as given by manufactures for both the models. Considering the output of an ideal PV cell as a reference power, a comparison between both the presented Simulink models in terms of power difference has also been carried out. This comparison illustrates that less the difference, more is the power output of the model.

Table 4

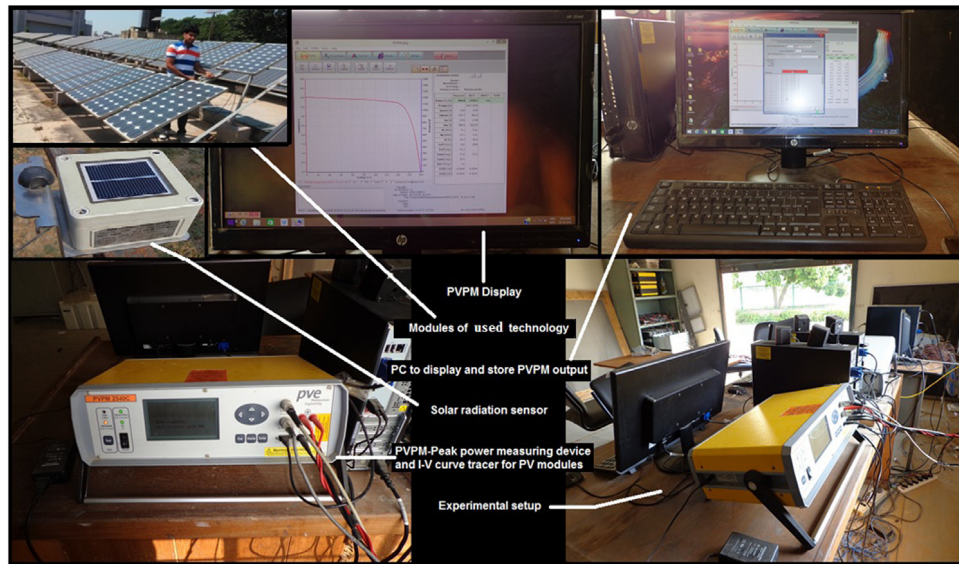
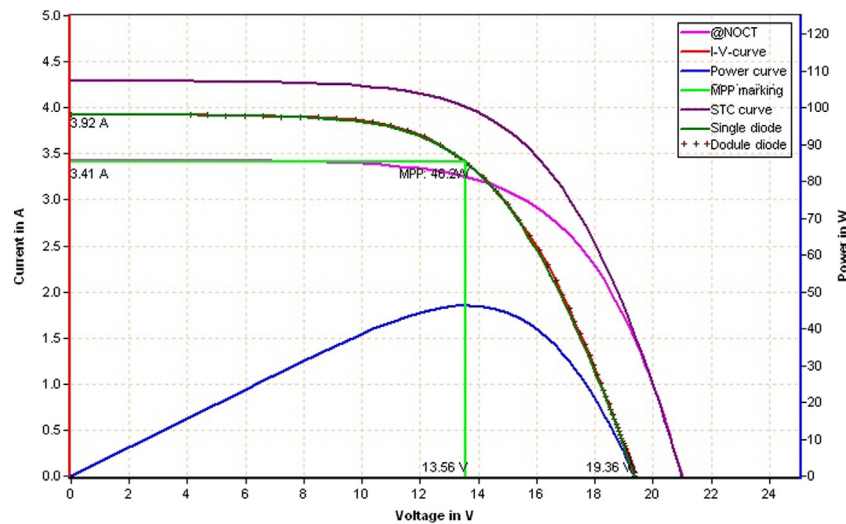
Field data measured under real operating conditions.

Date and time	PV module	$T_{\text{Module}} (^{\circ}\text{C})$	$T_{\text{Ambient}} (^{\circ}\text{C})$	Insolation (W/m^2)	P_{mp} (W)	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)
16-03-2016; 10:57:23 AM	MSX 60	47.019	43.464	915.354	46.230	13.561	3.409	19.361	3.921

Table 5

Field data measured under STC.

Cell technology	PV module	P_{mp} (W)	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)
Poly-crystalline	MSX 60	56.393	15.125	3.728	20.994	4.289

**Fig. 10.** Experimental set-up with Solarex MSX 60 module considered for the present study.**Fig. 11.** I - V and P - V curves under real operating conditions and comparison of I - V curve obtained under real operating condition with single and double diode based Simulink models of PV module.

7.3.1. Effect of cell temperature

The results obtained from Simulink models of single and double diode SPV module are compared to discuss the effect of temperature. Effect of cell temperature on single and two diode model on maximum output power P_m is investigated for a given value of incident insolation of $600 \text{ W}/\text{m}^2$ and the ideality factor for single diode model, $n = 1.2$, for double diode model, $n_1 = 1$ and $n_2 = 1.8$, with temperature variation from 0°C to 75°C . The results

obtained from simulation are shown in Fig. 15. It is observed that power decreases with an increase in temperature and the decrease in power is due to an increase in diode current (I_d). For single cell, V_m is cut down by about $1.75 \text{ mV}/^{\circ}\text{C}$, and for two cells it is found to be about $3.5 \text{ mV}/^{\circ}\text{C}$. The values of different parameters under temperature variation for single diode and two diode SPV models are given in Table 7.

The performance evaluation has been empowered by comparing the power output of single diode and double diode solar PV

Table 6
Characteristic values of single and double diode models.

Voltage V (V)	Double diode model		Single diode model	
	Current ' I_{double} ' (A)	Power ' P_{double} ' (W)	Current ' I_{single} ' (A)	Power ' P_{single} ' (W)
0	3.80	0.00	3.80	0.00
0.1	3.80	0.38	3.80	0.38
0.99	3.80	3.76	3.80	3.76
2.08	3.80	7.90	3.80	7.90
4.06	3.79	15.39	3.79	15.39
5.05	3.79	19.14	3.79	19.14
6.04	3.79	22.89	3.79	22.89
7.03	3.79	26.64	3.79	26.64
10	3.77	37.70	3.78	37.80
11.98	3.74	44.81	3.75	44.93
12.97	3.7	47.99	3.73	48.38
14.45	3.56	51.44	3.64	52.60
15.54	3.33	51.75	3.49	54.23
16.53	2.93	48.43	3.21	53.06
18.02	2.55	45.95	2.26	40.73
18.51	1.72	31.84	1.88	34.80
19.01	1.02	19.39	1.68	31.94
19.5	0.50	09.75	1.03	20.09
19.81	0.01	00.20	0.80	15.85
20.21	−0.93	−18.80	0.20	04.04
21.07	−2.03	−42.77	−0.03	−00.63

Table 7
Effect of temperature variation on single diode and two diode SPV model outputs.

Number of cells in series (N_s)	Temperature	0 °C	25 °C	50 °C	75 °C
36 (two diode)	P_m (W)	42.60	38.60	34.41	30.06
	V_m (V)	19.90	17.80	15.70	13.60
	I_m (A)	2.14	2.17	2.19	2.21
36 (single diode)	P_m (W)	52.41	46.41	40.50	34.69
	V_m (V)	24.00	21.40	18.90	16.40
	I_m (A)	2.18	2.17	2.14	2.12

Table 8
Effect of temperature on I_s , I_{rs} & I_{ph} .

S. No.	Temperature (°C)	Saturation current (I_s)	Reverse saturation current (I_{rs})	Photo-generated current (I_{ph})
1	25	1.406×10^4	1.406×10^4	3.949
2	30	2.538×10^4	1.666×10^4	3.957
3	35	4.499×10^4	1.964×10^4	3.965
4	40	7.837×10^4	2.303×10^4	3.973
5	45	1.342×10^3	2.687×10^4	3.981
6	50	2.263×10^3	3.119×10^4	3.989
7	55	3.757×10^3	3.605×10^4	3.997
8	75	6.993×10^2	6.860×10^4	4.052

Table 9
Effect of irradiance variation on single diode and two diode SPV model outputs.

Number of cells in series (N_s)	Irradiance (W/m ²)	1000	800	600	400
36 (two diode)	P_m (W)	59.23	46.71	34.19	26.30
	V_m (V)	16.10	16.10	16.10	18.40
	I_m (A)	3.68	2.90	2.12	1.43
36 (single diode)	P_m (W)	69.69	54.99	40.50	22.30
	V_m (V)	19.50	19.20	18.90	15.10
	I_m (A)	3.57	2.86	2.14	1.48

models operating under variable temperature with respect to the power output of an ideal PV model. Fig. 16 shows this comparison in terms of power difference between single and double diode model with respect to the ideal PV model at varying temperature ($P_{double} = 60 - 42.60 = 17.4 \text{ W/m}^2$ and $P_{single} = 60 - 52.41 = 7.59 \text{ W/m}^2$ at 0 °C).

The impact of the change in temperature over the saturation and reverse saturation current is presented below in Table 8. As the temperature of the cell increases, value of saturation and reverse

saturation current decreases. A demarcation in the saturation current occurs when the temperature varies from 40 to 45 °C while the reverse saturation current uniformly decreases. The change in the insolation has no impact over the change in saturation or reverse saturation current.

The calculated solar radiation considering temperature is provided as an input to the developed model and their effect on the I_{ph} is presented above in Table 8. It shows the change in the I_{ph} with a variation in the temperature. As the temperature increases

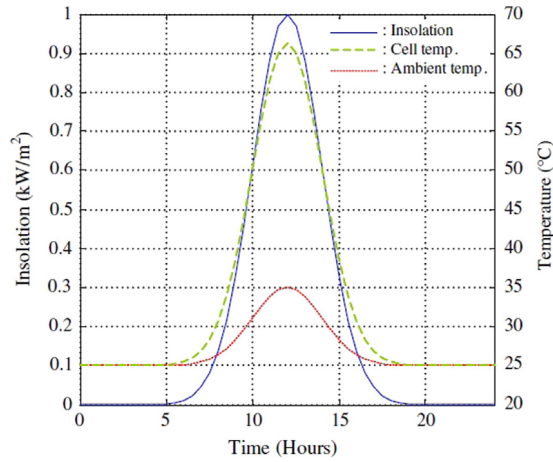


Fig. 12. Sunlight intensity, ambient and cell temperature in the form of Gaussian function for a sample day.

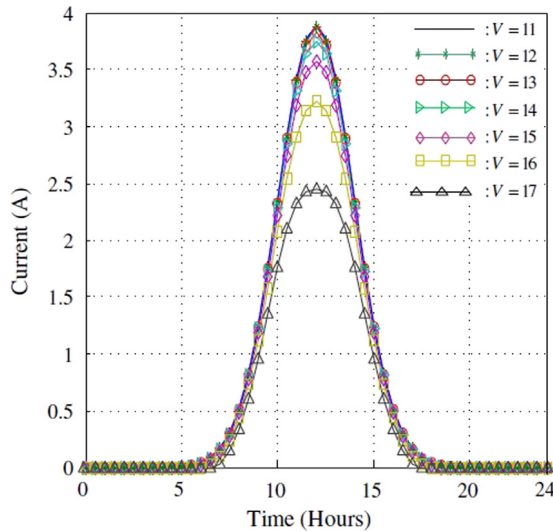


Fig. 13a. Current characteristics during a sample day for different voltage.

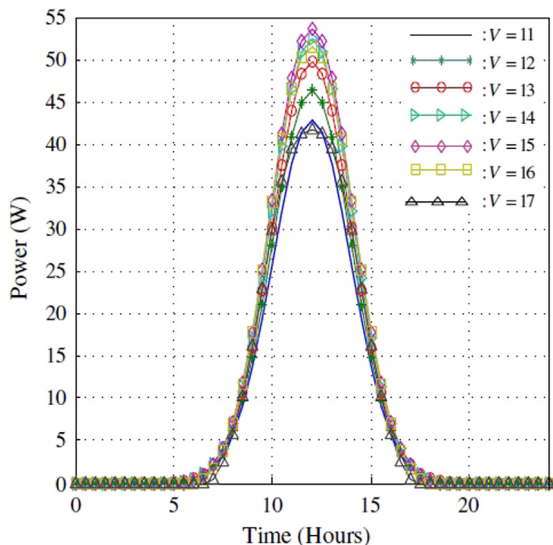


Fig. 13b. Power characteristics during a sample day for different voltages.

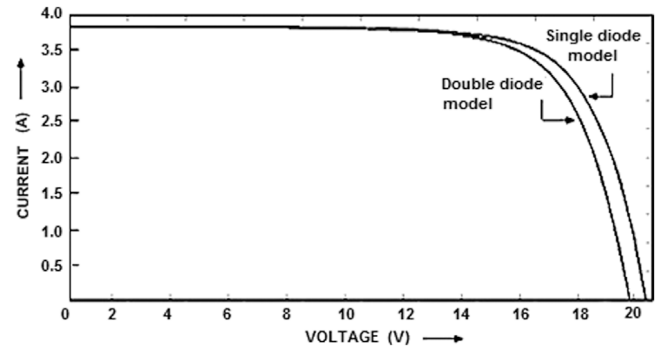


Fig. 14. I - V characteristics of single and double diode models.

the value I_{ph} slightly increases however the change in insolation on I_{ph} has a proportional effect.

7.3.2. Effect of irradiance

The outputs of single and double diode models are compared to identify the effect of variation in incident insolation. The characteristic I - V and P - V curves for single diode model and two diode models are obtained by varying the incident insolation and are shown in Fig. 17. In order to find out the effect of irradiance on the output of the module, the different values of irradiance considered are: 400 W/m², 600 W/m², 800 W/m², and 1000 W/m². The values of ideality factor (n) are taken as 1.2 for single diode model, for double diode model $n_1 = 1$ and $n_2 = 1.8$ and temperature is taken 25 °C respectively. It is observed that the current I_m is more affected by irradiance variation compared to its effect on voltage V_m . An increase in insolation levels leads to an increase in current I_m and the corresponding value of P_m also increases. The values of different parameters under insolation variation for single diode and two diode SPV models are given in Table 9.

Further, the power output of single diode and double diode solar PV models operating under variable insolation is compared with respect to the power output of an ideal PV cell. Fig. 18 shows this comparison in terms of power difference between single and double diode model with respect to the ideal PV model ($P_{double} = 60 - 26.30 = 33.7$ W/m² and $P_{single} = 60 - 22.30 = 37.7$ W/m² at 0 °C). This variation of power difference with decrease in insolation illustrates that the double diode model is more reasonable under low level insolation.

7.3.3. Effect of ideality factor

In order to observe the effect of ideality factor, temperature and irradiance values are kept constant at 25 °C and 600 W/m² respectively. I - V and P - V characteristics simulation results are obtained for different values of ideality factor, n of 1, 1.2, 1.3 and 1.5 as shown in Fig. 19. The values of different parameters under ideality factor variation for single diode and two diode SPV models are given in Table 10.

The power output of single diode and double diode solar PV models operating under varying ideality factor is compared with respect to the power output of an ideal PV cell. Fig. 20 shows this comparison in terms of power difference between single and double diode model with respect to the ideal PV model. The variation of power difference with increase in ideality factor illustrates that the effect of change in ideality factor on the output of single diode model is more as compared to the double diode model. The output power of single diode model gradually increases with increase in ideality factor as compared to the power output of double diode model.

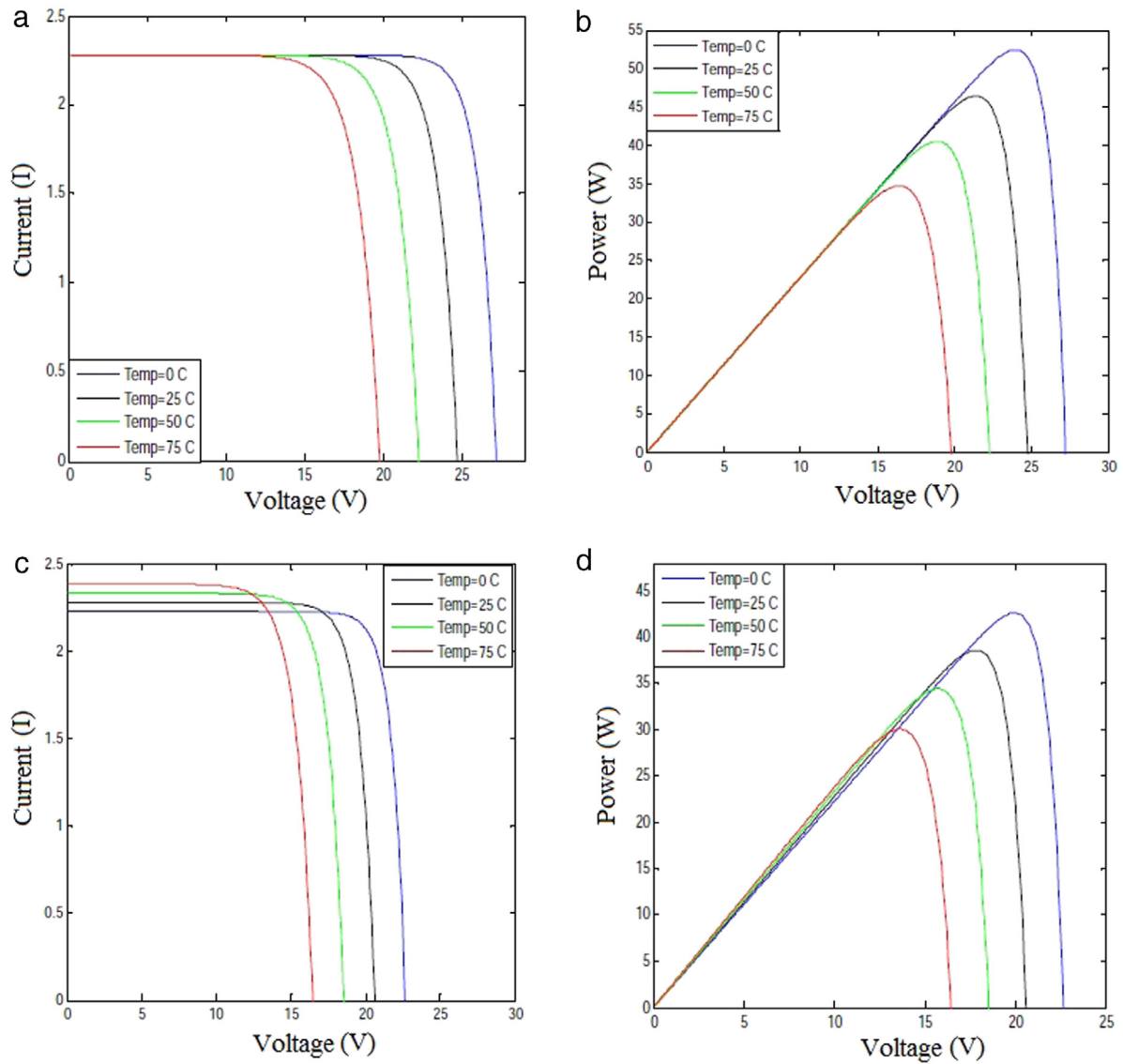


Fig. 15. Effect of cell temperature: (a) Single diode I - V characteristic curve, (b) single diode P - V characteristic curve, (c) two diode I - V characteristic curve, (d) two diode P - V characteristic curve.

Table 10

Effect of ideality factor on single diode and two diode SPV model outputs.

Number of cells in series (N_s)	Ideality factor n_1 and n_2	$n_1 = 1$	$n_1 = 1.2$	$n_1 = 1.5$	$n_1 = 1.8$
		$n_2 = 1.2$	$n_2 = 1.2$	$n_2 = 1.2$	$n_2 = 1.2$
36 (two diode)	P_m (W)	34.41	39.65	41.37	41.47
	V_m (V)	15.70	18.10	18.90	18.90
	I_m (A)	2.19	2.19	2.19	2.19
36 (single diode)	P_m (W)	33.75	40.50	43.87	50.62
	V_m (V)	15.70	18.90	20.50	23.60
	I_m (A)	2.15	2.14	2.14	2.15

Table 11

Effect of ideality factor on single diode and two diode SPV model outputs.

Number of cells in series (N_s)	Series resistance (R_s)	0.39	0.1	0.01	0.001
36 (two diode)	P_m (W)	8.47	25.52	39.63	41.18
	V_m (V)	11.01	13.01	18.01	19.01
	I_m (A)	0.77	1.96	2.20	2.17
36 (single diode)	P_m (W)	5.92	18.90	32.05	33.27
	V_m (V)	9.10	10.10	15.10	16.10
	I_m (A)	0.65	1.87	2.12	2.07

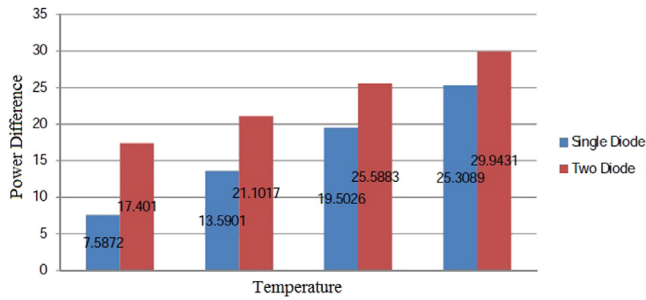


Fig. 16. Comparison of power output of presented models with a standard output power at different temperature levels.

7.3.4. Effect of series resistance

Under the present study, outputs of single and double diode models are compared to analyze the effect of series resistance (R_s). R_s values are taken as 0.39 (calculated), 0.1, 0.0 and 0.001 ohms and their effect on maximum power output is investigated as shown in Fig. 21. Irradiance value is kept at 600 W/m², temperature at 25 °C and ideality factor n at 1.2. The value of incident insolation corresponds to $I_{phc} = 3.8$ A. The figure illustrates that the output power of single and double diode models increases as the value of

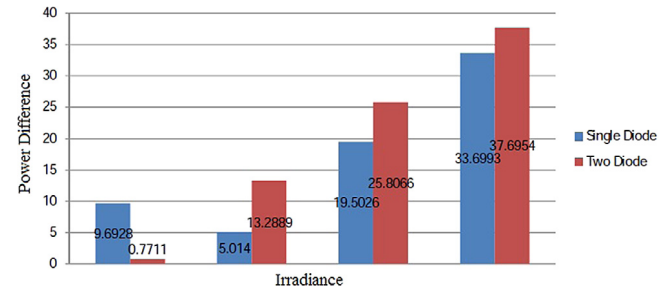


Fig. 18. Comparison of power output of presented models with a standard output power at varying irradiance.

R_s decreases. However, the output power of double diode model is found to be higher as compared to the single diode model for each corresponding value of R_s as shown in Table 11.

The difference of power with respect to variation in series resistance is demonstrated in Fig. 22. As the value of series resistance (R_s) is increased, the difference of power output of double diode model is reduced. This power difference value of double diode model is found to be less than the single diode model, i.e. the power output of double diode model is more than single diode model.

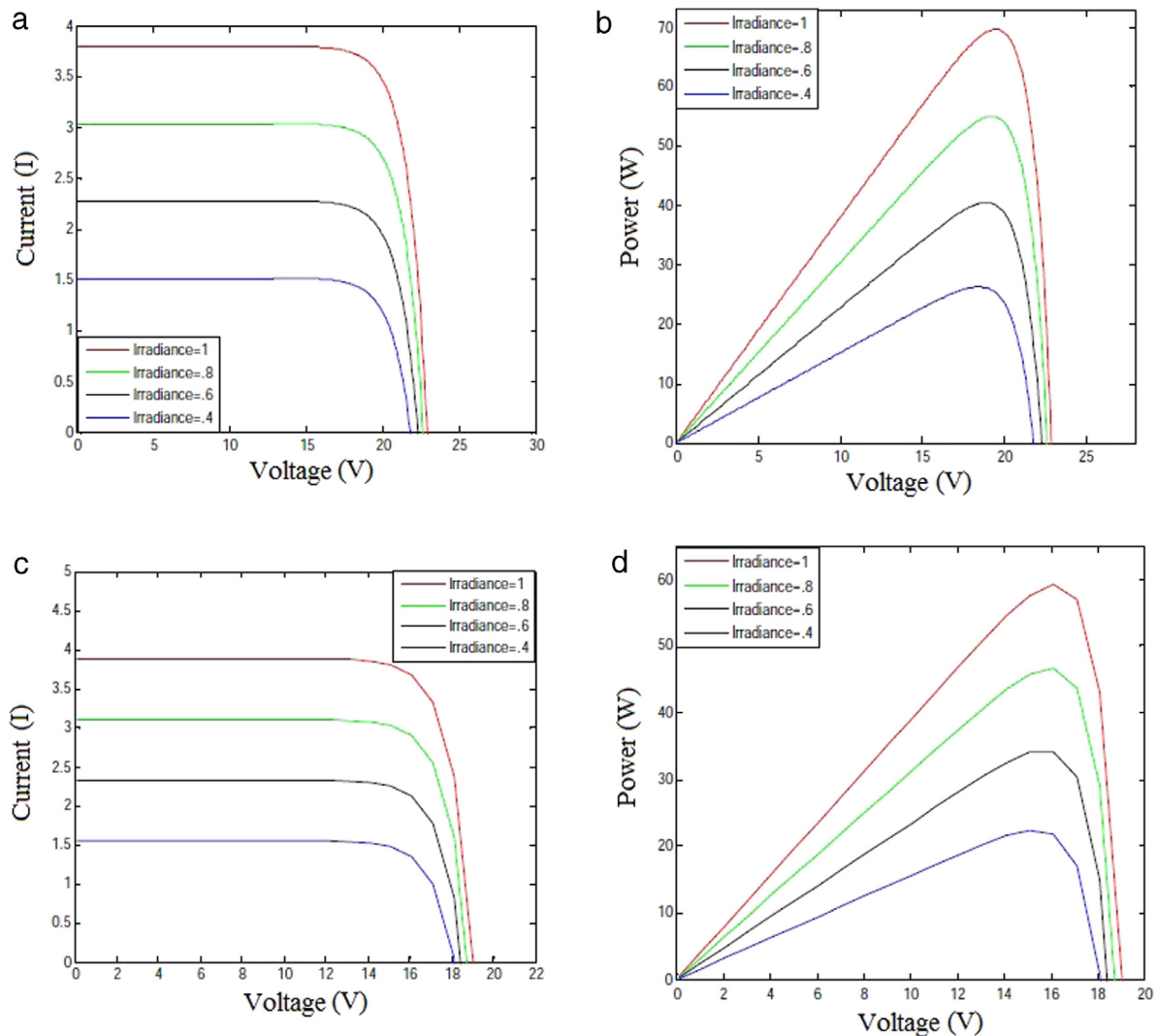


Fig. 17. Effect of insolation: (a) single diode I - V characteristic curve, (b) single diode I - V characteristic curve, (c) two diode P - V characteristic curve, (d) two diode P - V characteristic curve.

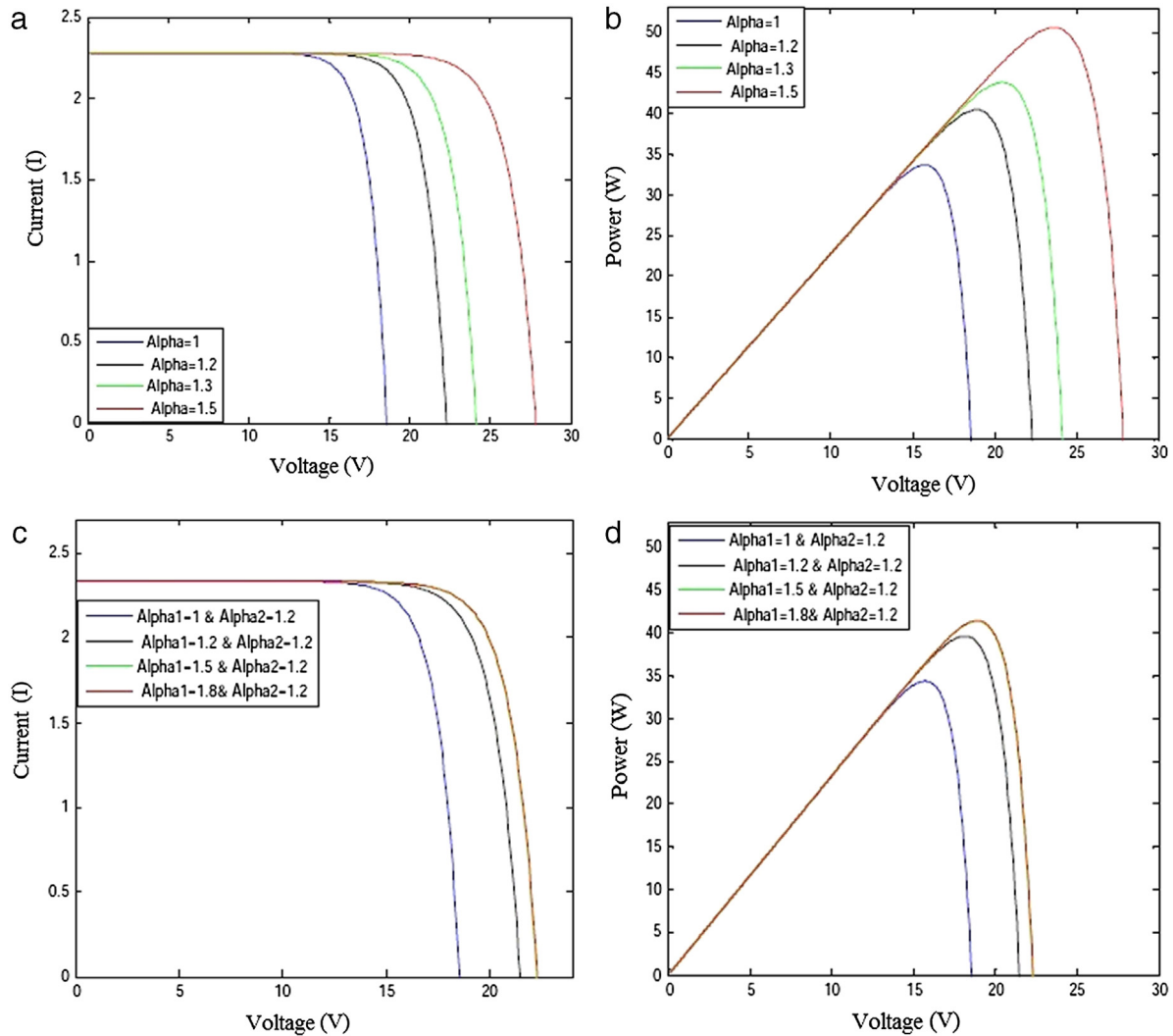


Fig. 19. Effect of ideality factor: (a) Single diode I - V characteristic curve, (b) single diode P - V characteristic curve, (c) two diode I - V characteristic curve, (d) two diode P - V characteristic curve.

Table 12
Effect of shunt resistance on single diode and two diode SPV model outputs.

Number of cells in series (N_s)	Series resistance (R_s)	1000 Ω	100 Ω	10 Ω	1 Ω
36 (two diode)	P_m (W)	8.47	10.91	12.98	15.47
	V_m (V)	11.01	13.01	14.01	17.01
	I_m (A)	0.77	1.96	2.20	2.17
36 (single diode)	P_m (W)	5.92	7.89	8.02	10.76
	V_m (V)	9.10	10.10	11.12	12.92
	I_m (A)	0.65	1.87	2.12	2.07

7.3.5. Effect of shunt resistance

Under the present study, outputs of single and double diode models are compared to analyze the effect of shunt resistance (R_{sh}). R_{sh} values are taken as 1000, 100, 10 and 1 Ω and their effect on maximum power output is investigated as shown in Fig. 23. The figure illustrates that the output power of single and double diode models increases with increase in the value of R_{sh} . However, the output power of single diode model is found to be higher as compared to the double diode model for each corresponding value of R_{sh} as shown in Table 12.

The difference of power with respect to variation in series resistance is demonstrated in Fig. 24. As the value of shunt resistance (R_{sh}) is increased, the difference of power output of double diode model is increased. This power difference value of double diode model is found to be more than the single diode model, i.e. the

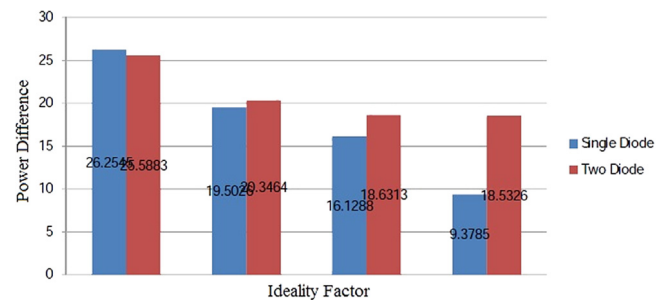


Fig. 20. Comparison of power output of presented models with a standard output power with changing ideality factors.

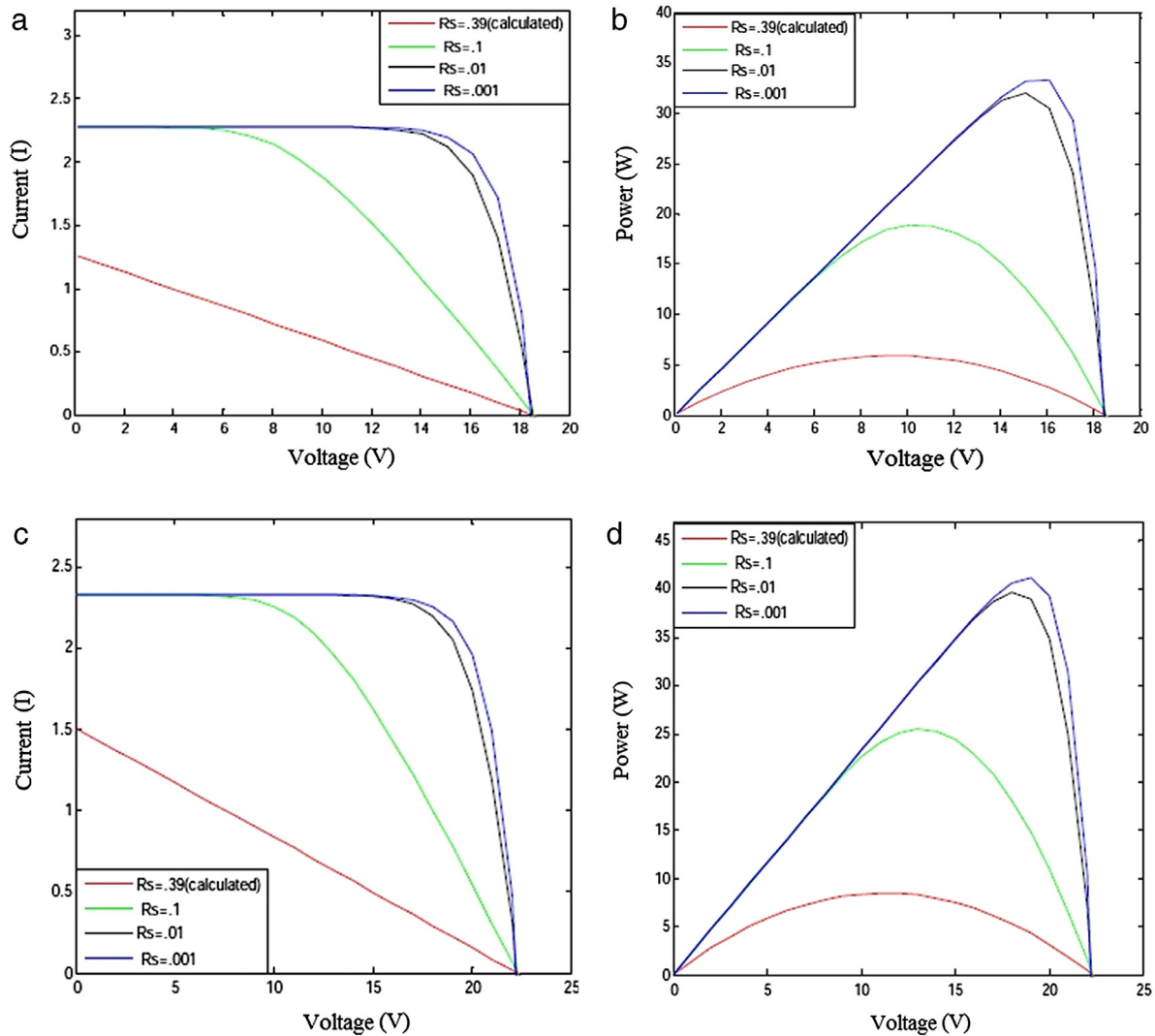


Fig. 21. Effect of R_s (a) single diode I - V characteristic curve, (b) single diode P - V characteristic curve, (c) two diode I - V characteristic curve, (d) two diode P - V characteristic curve.

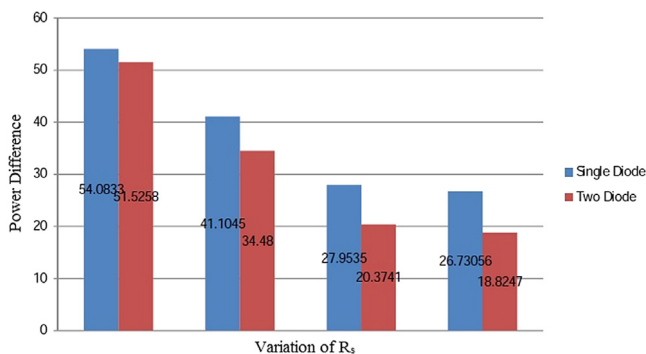


Fig. 22. Comparison of power output of presented models with a standard output power with varying series resistance.

power output of double diode model is less than single diode model as the value of shunt resistance (R_{sh}) is increased.

8. Conclusions

The proposed modeling of single and double diode models is done on the basis of their equivalent circuits. The study is carried out under the real operating conditions as well as under

controlled atmospheric conditions in order to investigate the effect of varying atmospheric conditions. Also the effect of parameters such as varying ideality factor (n) series resistance (R_s) and shunt resistance (R_{sh}) are investigated to determine the difference in power generated for both the models with respect to ideal PV module. The fill factor and efficiency of a solar cell decreases due to both shunt and series resistance losses. The utilization of iterative method guides us to definite values of photo-generated current (I_{ph}), ideality factor (n), series resistance (R_s) and shunt resistance (R_{sh}). It is found that the output power of PV module is extensively affected even with a small variation in series resistance (R_s), thus this value is kept very small. This comparison empowers the outcome of this study. The final outcomes establish the accuracy of double diode model over the single diode model under low intensity insolation (or shading). On the other hand, single diode confirms the effectiveness under high insolation levels. Findings of this study could be very helpful in selecting the appropriate model under given operating conditions.

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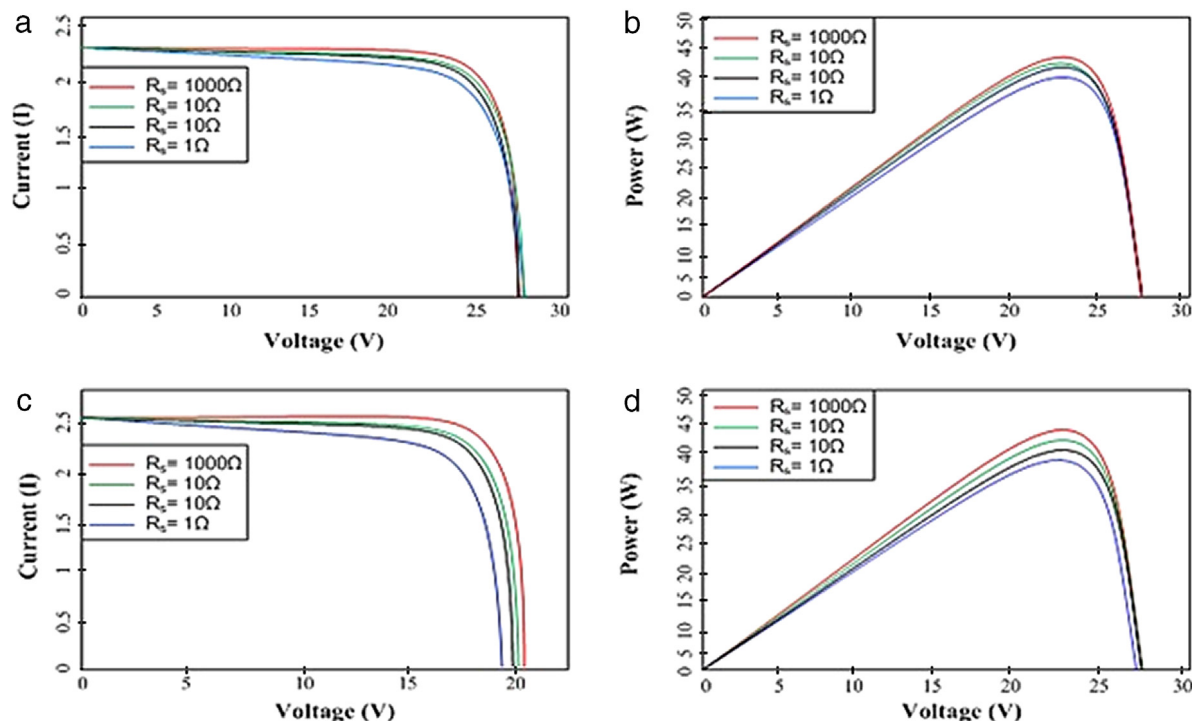


Fig. 23. Effect of R_{sh} (a) Single diode I - V characteristic curve, (b) single diode P - V characteristic curve, (c) two diode I - V characteristic curve, (d) two diode P - V characteristic curve.

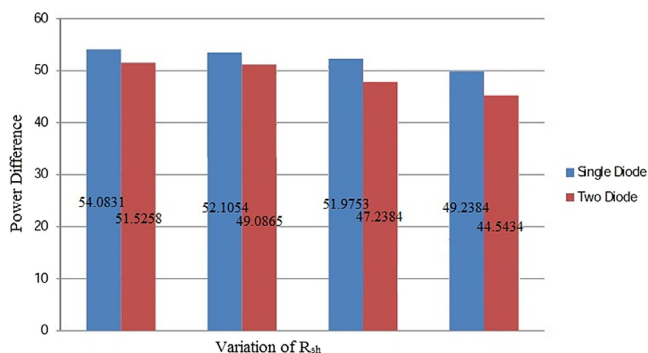


Fig. 24. Comparison of power output of presented models with a standard output power with varying series resistance.

and National Institute of Solar Energy (NISE, Gurgaon under MNRE, Government of India), India.

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