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A novel and accurate photovoltaic simulator based on seven-parameter model

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ABSTRACT

The output characteristics of a photovoltaic (PV) array are highly non-linear. Therefore, an accurate and efficient PV model is required to study and analyze the operation of PV system in the changing environmental conditions. This paper proposes a precise PV simulator based on the seven-parameter electric circuit model. The proposed simulator can generate the output characteristics of a PV system precisely at different operating conditions. It has also enough flexibility to simulate different configurations of PV panels with series/parallel connections. The robustness of the proposed simulator is demonstrated under the partial shaded conditions. Additionally, the performance of the developed simulator is verified by interfacing it with the actual power electronic converter and maximum power point tracking (MPPT) controller. The proposed PV simulator will facilitate the design aspects of PV systems and help in behavior assessment of newly developed controllers prior to practical implementation.

1. Introduction

The demand of electrical energy is increasing day by day and the world is more concern about the high oil prices, fossil fuel deficit, global warming and environmental damages. The participation of renewable and green energy sources in the generation of electrical energy is indispensable now-a-days. Among the renewable energy sources, solar energy is the most promising and photovoltaic (PV) system provides the most direct method to convert solar energy into electrical energy. Despite of the intermittency of sunlight, many PV system have been developed in different countries of the world because of its long term benefits, benevolent fed in tariff initiatives and other schemes offered by governments to encourage the use of renewable energy sources (RES). The world's cumulative installed capacity of PV was 23GW in year 2009 [1]. In 2011, more than 69GW of PV power is installed worldwide that can generate 85 TWh of electricity per year [1]. Among all RES the growth rate of PV power is incomparable and reached almost 70% in year 2011 [1]. The large penetration of PV power into the electricity grid would have adverse effects on electrical power system. To study these effects and to design power electronic converters and MPPT controllers, an efficient and accurate model of PV is required.

The output of PV is extremely non-linear and it is not suitable to represent it with a constant or controlled voltage/current source. Several PV electrical models have been proposed and developed in literature [2–7]. Some of these models are described vaguely and some of them are much complex for the simple power system studies. The simplest model is temperature and radiation scaling of maximum power point which requires the temperature and irradiation coefficients of MPP and predicts the performance of PV only at one point [2]. In [3,4] a method of translation of *I*–*V* curve from one environmental condition to another was presented. Bilinear interpolation method is presented that requires four practically determined *I*–*V* curves, two at different insolations and two at different temperatures [4]. These models are quite complex and require a large amount of data that is not usually provided by the manufacturers. The most efficient and practical model for PV is developed in Sandia Lab [5]. This model takes three inputs that are temperature, irradiation and wind speed and computes the voltage and current of PV at five main points on the *I*–*V* curve. This model also requires thirty practically determined coefficients to simulate the behavior of any PV panel [5]. Values of these coefficients are available for a large number of commercial PV panels [6]. Due to the complexity of these models power system studies such as load flow, maximum power point tracking, and load frequency matching become difficult and require large computational time. Electrical characteristics of PV can be modeled by representing it with equivalent electrical circuit [7]. This model has advantage over the other models due to its electrical circuit nature and behavior of PV can

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be easily understood and investigated. It is very suitable for the dynamic and transient study of the power electronic converters.

The electric circuit based model of PV is further classified as an ideal diode model, four-parameter model, five-parameter model and two-diode model. These models are different from each other in accuracy and implementation. The simplest among these models is the ideal diode model which consists of a single diode and irradiation dependent current source [8,9]. Performance of this ideal model is enhanced by means of series resistance and it is generally known as four-parameter model [10,11]. This model is easy to implement and provides acceptable results. However, its performance deteriorates at high temperatures and low irradiation [12] and also for thin film technology based PV panels [13]. To overcome these shortcomings, an improved circuit based model is developed by adding shunt resistance and it is widely known as five-parameter model [13–15]. Comparison of four and five-parameter model is done in [16] for mono-crystalline PV panel and showed that the five-parameter model is more efficient in estimating the operating current and power at different atmospheric conditions. To further improve the efficiency of the circuit based model some authors used the two-diode model [12,17]. The model non-linearity and the number of parameters to be computed during simulation are increased by inclusion of an extra diode that will make the model computationally inefficient. The competency of the two-diode model over four- and five-parameter models is shown in [12]. To make the model computationally efficient, values of some parameters are assumed constant which deteriorate its performance under the partial shading condition. Five-parameter model is a good compromise between accuracy and simplicity as given in [18].

Recently, seven-parameter model has been proposed in [19] in which efficiency of five-parameter is further improved by adding two additional parameters and without compromising its computational efficiency. Authors have modified the translational equations by adding two exponential constants and showed that the model accuracy has been enhanced and given it the name of seven-parameter model.

There is a need of an accurate and generalized PV simulator that can generate output characteristics of a PV panel or a large PV array precisely at different operating conditions, including the non-uniform irradiation condition. It should be able to work in conjunction with power electronic converters and MPPT controllers for their design and control. Several PV simulators have been presented in the literature based on different PV models discussed above [15,20–24]. Most of these are developed in MATLAB script file and implemented in Simulink using S-function block and some of them can simulate only a single PV panel. Furthermore, very few of them have shown their working under partial shaded condition [23,24].

In this paper, a generalized PV simulator is proposed and developed using the very accurate seven-parameter PV model. To the best of authors' knowledge, such simulator is proposed for the first time. It is employed using only the blocks of the Simulink and have resemblance with the actual PV electric circuit model, which will facilitate the design engineers and researchers in understanding the overall PV power system. Similar to Simulink blocks, the proposed simulator is implemented as a masked block and prompts the user to enter attributes of the PV array under consideration. The effectiveness of the proposed simulator is investigated under different operating conditions including the harsh partial shaded condition. The robustness of the proposed simulator is analyzed in conjunction with the DC–DC converter and MPPT controller. It is envisaged that the developed simulator can be very helpful for the PV design engineers in the simulation study before any experimental verification. Additionally, detailed electrical modeling of PV panel and PV array is also discussed.

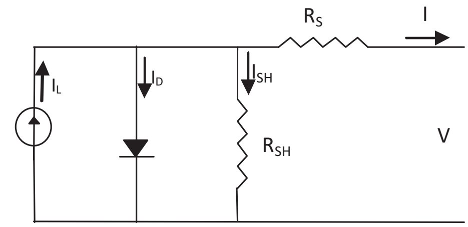


Fig. 1. PV electric circuit model.

The rest of this paper is described as follows. In Section 2, electrical modeling of a PV is discussed that includes a comprehensive PV panel and PV array modeling. MATLAB/Simulink implementation of this model is presented in Section 3. It is followed by results and discussion in Section 4 and conclusion is made in Section 5.

2. PV modeling

Commercially available PV is in the form of PV panels. Maximum output power of a single PV panel is in the range of tens of Watts to some hundreds of Watts that would be acceptable for the small-scale applications. For large-scale applications, however, series and parallel combinations of these panels are needed to enhance the PV output power. Connecting PV panels in series increases the current capability of PV source and parallel connection increases the voltage rating of PV source. This series/parallel combination of PV panels is commonly known as PV array. Considering the importance of PV panel as a basic unit of PV array, model of the PV panel is developed which is then modified to stand for a complete PV array.

2.1. PV panel modeling

The seven-parameter electric circuit model of PV is shown in Fig. 1. It consists of light depended current source, a p–n junction diode and two resistances one in series and another in shunt. Seven parameters are defined as:

I_L	Light generated current
I_0	Diode saturation current
R_S	Series resistance
R_{SH}	Shunt resistances
"a"	Diode modified ideality factor
"m"	Exponential constant for I_L
"n"	Exponential constant for "a"

where "m" and "n" are the two additional parameters and are exponential constants for "I_L" and "a", respectively and proposed in Ref. [19].

Using simple Kirchhoff's current law following relationship can be found:

$$I = I_L - I_D - I_{SH} \quad (1)$$

Here I_D and I_{SH} depicts the diode current and shunt branch current, respectively and given by;

$$I_D = I_0 \left\{ \exp\left[\frac{(V + IR_S)}{a}\right] - 1 \right\} \quad (2)$$

$$I_{SH} = \frac{V + IR_S}{R_{SH}} \quad (3)$$

Putting these expressions of I_D and I_{SH} into Eq. (1) gives the complete I–V characteristics of a PV panel;

$$I = I_L - I_0 \left\{ \exp\left[\frac{(V + IR_S)}{a}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}} \quad (4)$$

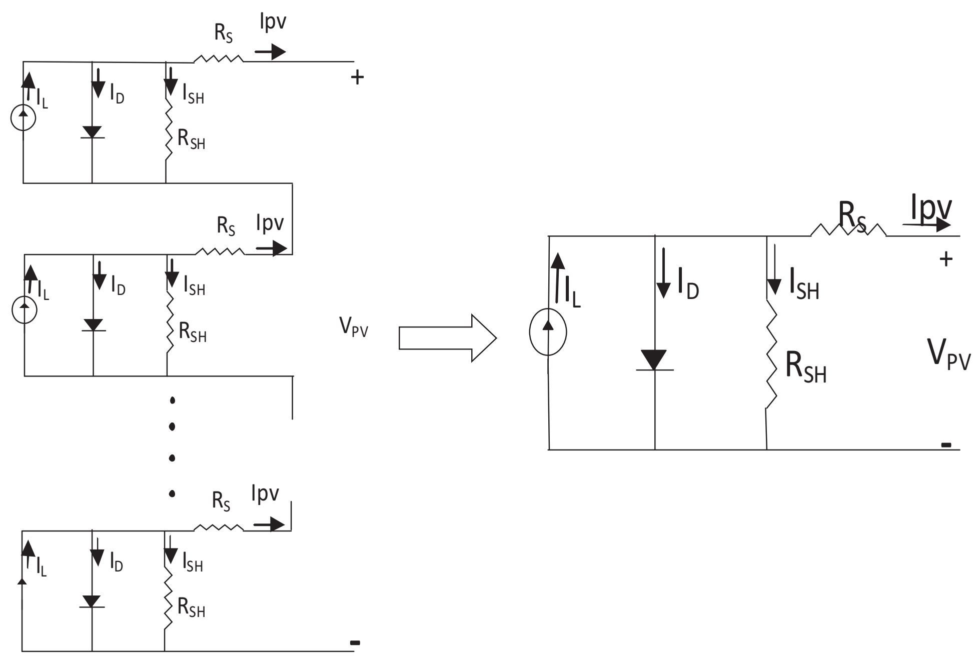


Fig. 2. Panels connected in series in an array.

where I and V represent the current and voltage generated from the PV panel. Modified ideality factor "a" is given by;

$$a = \frac{N_s a' kT}{q} \tag{5}$$

where N_S is the number of cell in the PV panel, "a'" is the ideality factor (it has value between 1 and 2 for real diode), k is the Boltzmann's constant, T is the cell temperature and q is the electronic charge.

Eq. (4) shows the I–V characteristics of a PV panel and governed by five parameters (I_L, I_0, R_S, R_{SH} and "a"). Having the five parameters known, Eq. (4) can be solved. With different atmospheric conditions, these parameters have different values that can be calculated at any ambient condition using the translational Eqs. (6)–(11) assuming their values at standard test conditions (STC) (25 °C, 1000 W/m^2) are known.

$$a = a_{ref}\left(\frac{T_c}{T_{c,ref}}\right)^n \tag{6}$$

$$I_L = \left(\frac{S}{S_{ref}}\right)^m [I_{L,ref} + \mu_{I,sc}(T_c - T_{c,ref})] \tag{7}$$

$$R_{SH} = R_{SH,ref}\frac{S_{ref}}{S} \tag{8}$$

$$R_S = R_{S,ref} \tag{9}$$

$$\frac{I_0}{I_{0,ref}} = \left(\frac{T_c}{T_{c,ref}}\right)^3 exp\left(\left(\frac{N_s * T_{c,ref}}{a_{ref}}\right) * \left(\frac{E_{g,ref}}{T_{c,ref}}\left|-\frac{E_g}{T_c}\right|\right)\right) \tag{10}$$

$$\frac{E_g}{E_{g,ref}} = 1 - C(T_c - T_{c,ref}) \tag{11}$$

where m and n represents the additional two parameters and are exponential constants for "I_L" and "a", respectively. S and T_c represent the solar radiation and temperature of the PV panel, respectively. $\mu_{I,sc}$ is the temperature coefficient of short circuit current and provided by the manufacturer. Eg is the band-gap energy of the PV cell material and C = 0.0003174 [25]. Quantities with the subscript "*ref*" represent their values at the STC. The values of these seven parameters at reference condition are calculated using the translational equations and the data provided by the manufacturer [19].

2.2. PV array modeling

As discussed earlier PV panels can be grouped in different modes to form PV arrays. Some topologies are series array, parallel array, series–parallel array and total cross-tied array. Among these topologies series–parallel array is the most commonly used because of its flexibility in maintaining the required output voltage and current with better performance in the partial shaded conditions [26]. Eq. (4) can be modified to represent the I–V relationship of series–parallel array and written as:

$$I = Npp * I_L - Npp * I_0\left\{\exp\left[\frac{(V + IR_S(Nss/Npp))}{Nss * a}\right] - 1\right\} - \left(\frac{V + IR_S(Nss/Npp)}{(Nss/Npp)R_{SH}}\right) \tag{12}$$

where I_L, I_0, R_S, R_{SH}, "a" are parameters of single PV panel. N_{SS} and N_{PP} represent the number of panels connected in series and parallel, respectively. It can be noticed that N_{PP} is multiplied with the current associated terms to enhance the current output of PV system and, similarly, N_{SS} is multiplied with voltage related terms to increase the voltage output of PV. A theoretical illustration of a series and parallel connection of PV panels is shown in Figs. 2 and 3, respectively. These figures depicts that the circuit elements of combined panels can be merged together to form a single equivalent model that is similar to circuit of one PV panel [27]. Expressions for the array parameters in relation with the panel parameters are given in Table 1. The exponential constants, m and n, will remain the same.

Panels are linked in parallel to increase current rating, the values of I_{SH}, I_{MP}, I_L and I_0 are altered and multiplied with a number of parallel connected panels. The factor "a", V_{OC}, V_{MP} remains unchanged. While the R_S and R_{SH} are divided by the number of parallel connected panels. Similarly, for panels connected in series to enhance voltage rating, values of V_{OC}, V_{MP} and factor "a" are multiplied with the number of series connected panels. Values of I_{SH}, I_{MP}, I_L and I_0

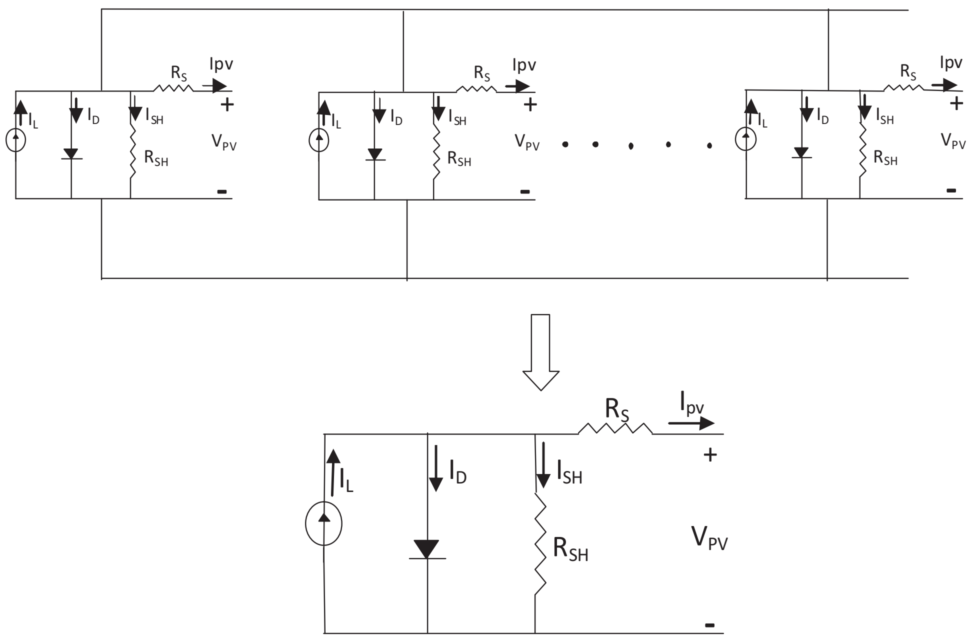


Fig. 3. Panels connected in parallel in an array.

Table 1
Array parameters expressions in association with panel parameters.

Panel parameter	Modified array parameters	Panel parameter	Modified array parameters
V_{OC}	V_{OC}*N_{SS}	I_L	I_L*N_{PP}
I_{SC}	I_{SC}*N_{PP}	I_0	I_0*N_{PP}
V_{MP}	V_{MP}*N_{SS}	R_S	R_S*(N_{SS}/N_{PP})
I_{MP}	I_{MP}*N_{PP}	R_{SH}	R_{SH}*(N_{SS}/N_{PP})
n	n*N_{SS}	a	a*N_{SS}

V_{OC} is open circuit voltage, I_{SC} short circuit current, V_{MP} and I_{MP} are the voltage and current at maximum power point, respectively.

remain unaltered and R_S and R_{SH} are multiplied by the number of series connected panels.

3. Modeling of PV simulator

3.1. Simulator design

A PV simulator is implemented in MATLAB/Simulink and its block representation is shown in Fig. 4(a). Inputs to the simulator are irradiation, S, and temperature, T, and output is the +ve and −ve terminals which can be used to connect PV simulator to power system. Fig. 4(b) shows the internal circuitry and the last stage of the modeling. It depicts that the implemented circuit is quite similar to the PV electric circuit model and consists of light dependent current source, p–n junction diode, and series and shunt resistances. This stage contains other subsystems that are connected together to execute *I–V* characteristics of PV. These subsystems are not shown for brevity.

It is implemented as a mask block just like the other MATLAB/Simulink blocks and prompts user to enter the necessary parameters of the PV to be executed. Parameters required are: number of cells in PV panel, NC, open circuit voltage, VOC, short circuit current, ISH, voltage at maximum power point, VMP, current at maximum power point, IMP, temperature coefficients for voltage and current, $\mu_{V,OC}$ and $\mu_{I,SC}$, number of series-connected panels, NSS, and parallel-connected panels, NPP, in an array. A sample of block parameters of PV simulator is shown in Fig. 5.

3.2. Partial shading

The partial shaded condition of PV can be implemented by placing PV simulator block in series with each other and connecting

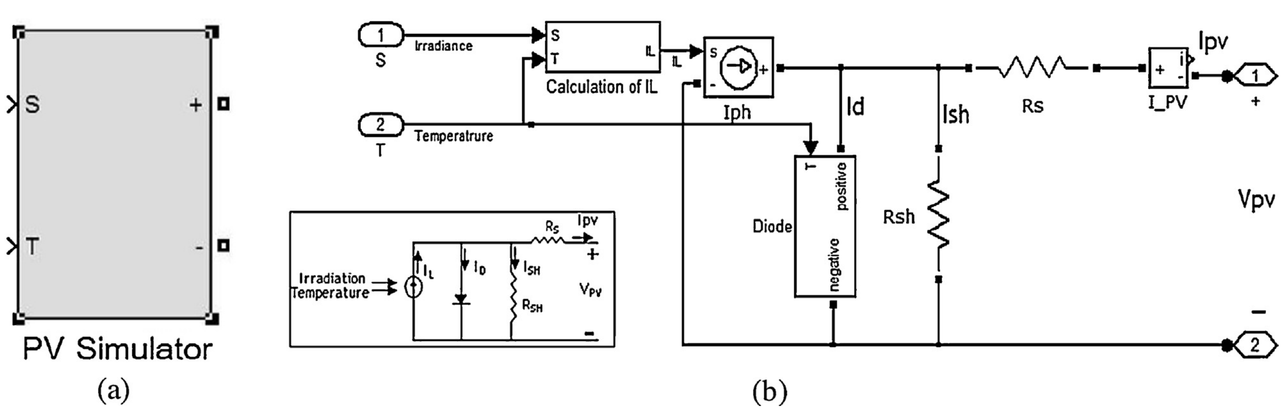


Fig. 4. Implementation of PV simulator in Simulink: (a) PV simulator block. (b) Internal circuit of the PV simulator block.

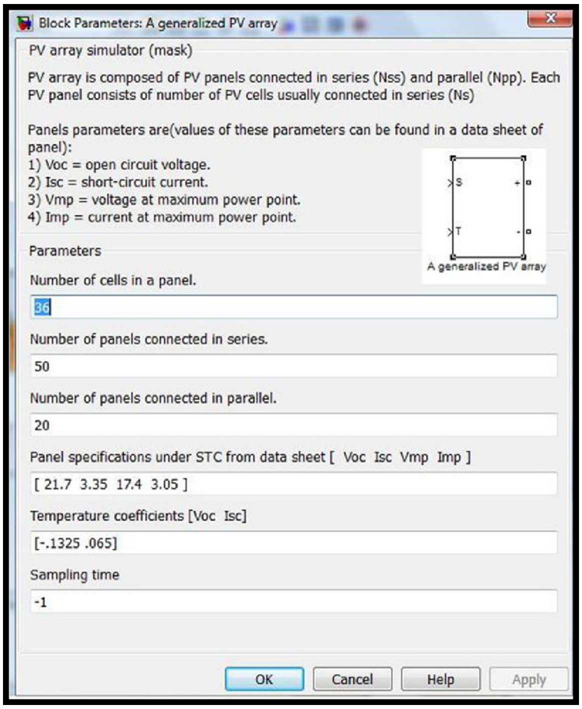


Fig. 5. Block parameters window of PV array simulator in Simulink.

a bypass diode in anti-parallel configuration with each block as shown in Fig. 6. The number of series connected simulator blocks required depends on the number of shaded patterns to be considered. For instant, Fig. 6 shows three PV simulator blocks connected in series and can carry out the simulation of three different shading patterns. It can also be used to simulate the PV array at different temperature conditions. This generalizes the proposed simulator to emulate PV panel, PV array, and partially shaded arrays with user defined shading patterns.

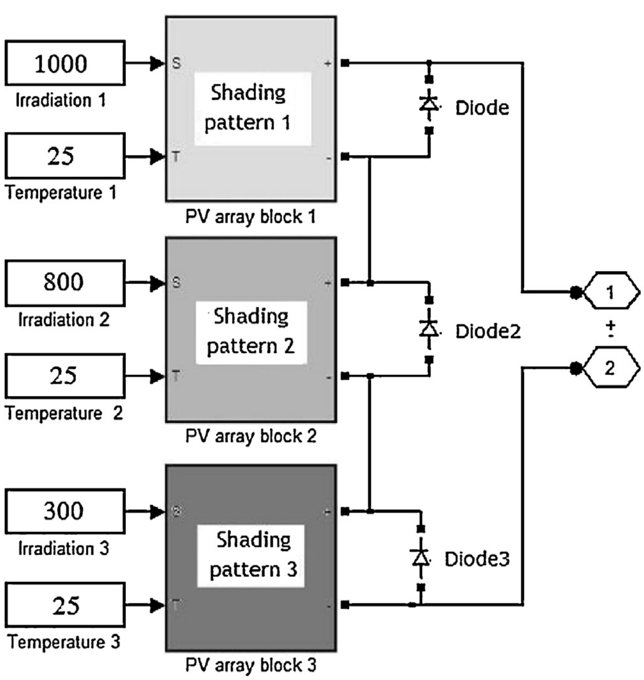


Fig. 6. Partial shaded implementation of PV array simulator in Simulink.

Table 2
Specification of selected PV panels taken from data sheet.

Parameter	m-Si (Sunpower)	CIS shell ST36
Open circuit voltage (V_{OC})	48.7 V	22.9 V
Short circuit current (I_{SC})	5.99 A	2.68 A
Max. power voltage (V_{MP})	41 V	15.8 V
Max. power current (I_{MP})	5.61 A	2.28 A
Max. Power (P_{MP})	230 W	36 W
No. of cells in series (N_S)	72	42
I_{SC} temperature coefficient	3.5 mA/C	3.2 mA/°C
V_{OC} temperature coefficient	−132.5 mV/°C	−100 mV/°C

4. Results and discussions

Four different tests were conducted to verify the correctness and effectiveness of the proposed PV simulator.

4.1. Test 1: efficiency test

The efficiency of the developed PV simulator is validated by comparing the determined curves generated by the developed PV simulator with the experimental curves. The experimental curves data is extracted from the PV panel datasheets using digitizer software. Two PV panels of different technologies are used for this purpose; these are mono-crystalline (m-Si) [28] and thin film (CIS) [29]. The specifications of these technologies are given in Table 2. Table 3 shows the values of seven parameters calculated using the multi-variable optimization technique, the Nelder–Mead simplex search algorithm [19].

Fig. 7 shows the determined *I–V* curves for mono-crystalline (m-Si) and thin film (CIS) panel for different irradiation levels and constant temperature of 25 °C. These figures illustrate that the *I–V* curves obtained from the proposed simulator are in great accordance with the experimental curves for all the irradiation levels. The accuracy of the proposed PV simulator encountered with temperature change is shown in Fig. 8 for both technologies. The performance of the proposed simulator is examined at 20 °C, 30 °C, 40 °C, 50 °C and 60 °C for thin-film. Since the experimental data of only 50 °C curve is available in the datasheet for mono-crystalline, it is tested at this temperature only. It can be seen that the curves generated from the proposed PV simulator matches greatly with the experimental curves under all the temperature variations.

Precision of the proposed simulator is verified by calculating statistically the root mean square error (RMSE) given by:

$$\mathrm{RMSE} = \frac{\sqrt{\frac{1}{n}\sum_{n}^{i=1}(y_i - x_i)^2}}{(1/n)\sum_{n}^{i=1} x_i} \tag{13}$$

where x and y represent the experimental and measured values, respectively and n is the number of points taken. RMSE is calculated for all the given operating conditions and it is determined for current values computed against the voltage at three

Table 3
Specifications of seven-parameter model.

Parameter	m-Si (Sunpower)	CIS shell ST36
Light current "I_L" (A)	5.97	2.6803
Saturation current "I_0" (A)	2.151e−7	4.11965e−05
Series resistance "R_S" (Ω)	.00796	1.3901
Parallel resistance "R_{SH}" (Ω)	89,546.41	38,544.6
Modified ideality factor "*a*"	2.6971	2.0662
Exponential constant of I_L "*m*"	.9865	1.1213
Exponential constant of '*a*' "*n*"	1.1056	0.9431

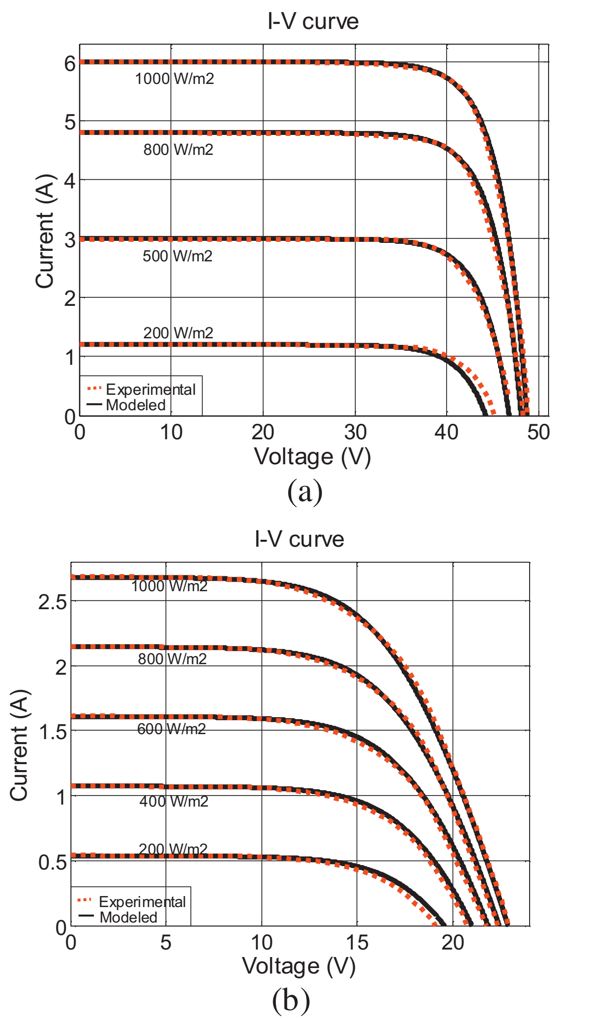


Fig. 7. *I–V* curves for different irradiations: (a) mono-crystalline (m-Si) and (b) thin-film (CIS) under constant temperature.

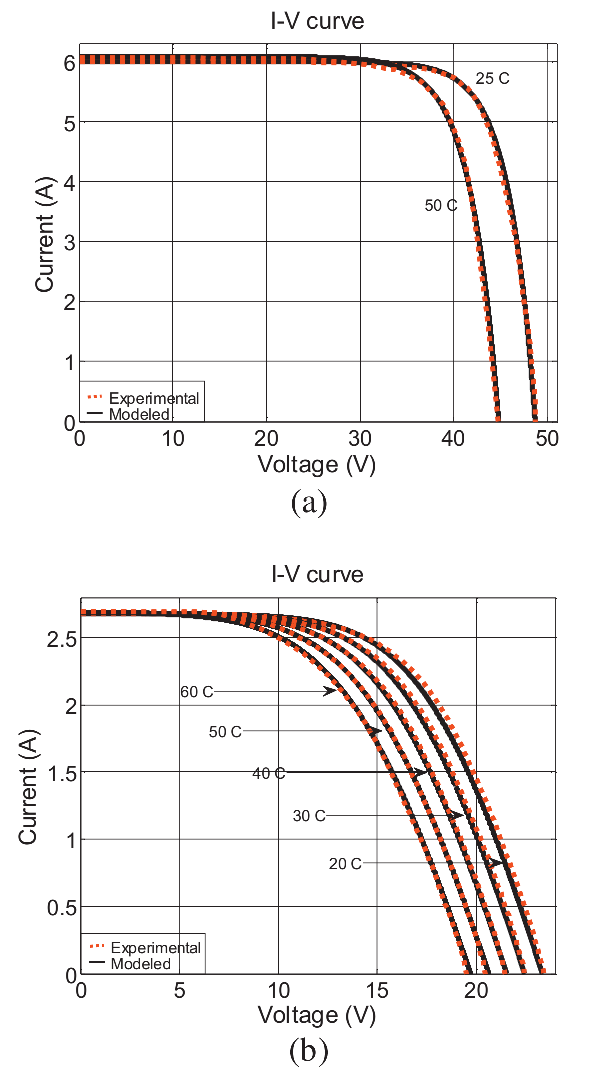


Fig. 8. *I–V* curves for different temperatures: (a) mono-crystalline (m-Si) and (b) thin film (CIS) under constant irradiation.

different points on the *I–V* curve, i.e., open circuit point, short circuit point and maximum power point. Fig. 9 shows the RMSE values of *I–V* curves for different irradiation and temperature. It can be noticed that errors are negligible for all the operating conditions and its values are increasing with the decrease in irradiation and increase in temperature and that is in consistent with [3,8].

Furthermore, the potential of the developed PV simulator is assessed against the PV model presented in Ref. [15]. Fig. 10 shows the performance comparison. It can be observed that the proposed model is more accurate compared to that presented in Ref. [15] as it follows the real curves with higher precision especially at low irradiation condition.

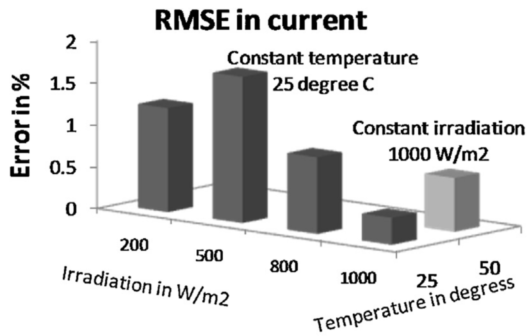
4.2. Test 2: performance as a large PV array

In this test working of the proposed PV simulator as a large PV array is examined under different operating conditions. PV array is composed of 50 series- and 20 parallel-connected panels of mono-crystalline (m-Si). The detailed specifications are given in Table 2. Fig. 11 shows the *I–V* curves of the considered PV array at different irradiation levels with constant temperature of 25 °C. Since the PV array has 20 panels in parallel, its short circuit current (I_{SC}) at STC becomes 20*5.99 = 119.8 A. In addition, its open circuit voltage (V_{OC}) at STC becomes 48.7*50 = 2435 V as it has 50 panels in series. It is also obvious from the graphs that the value of short circuit current (I_{SC}) is highly decreased and a value of open circuit voltage (V_{OC}) is slightly reduced by decreasing the irradiation level. Fig. 12 shows the *I–V* curves of assumed PV array at different temperatures and constant irradiation level of 1000 W/m^2. It is clear from the graphs that the *I–V* curve of the PV array are highly non-linear and short circuit current (I_{SC}) increased slightly and open circuit voltage (V_{OC}) decreased by increasing the cell temperature.

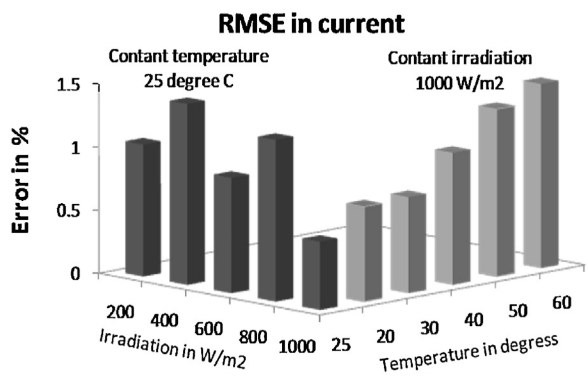
This test demonstrates that the proposed PV simulator can emulate a large PV array or PV power station and can generate its *I–V* curves at different irradiation and temperatures. As these operating conditions are continuously varying with time, the proposed simulator can be a valuable tool to analyze the impacts of these changing condition on the overall power system performance and response.

4.3. Test 3: PV performance under partial shading condition

In order to test the proposed PV simulator under partial shaded condition, PV array configuration of Fig. 6 is adopted. It consists



(a)



(b)

Fig. 9. RMSE for different irradiation and temperature: (a) mono-crystalline (m-Si) and (b) thin film (CIS).

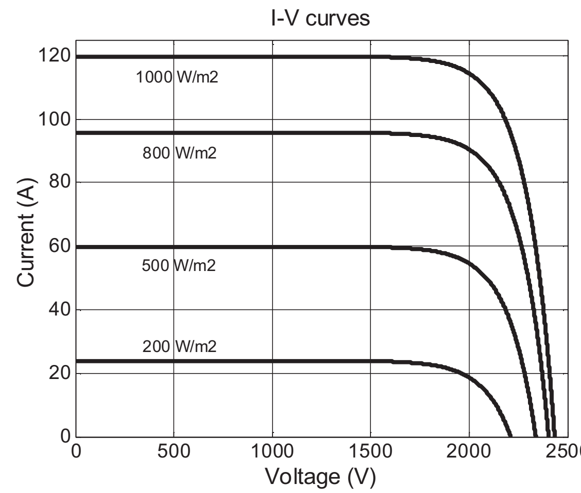


Fig. 11. *I–V* characteristics of PV array at different irradiation (W/m^2) and constant temperature of 25 °C.

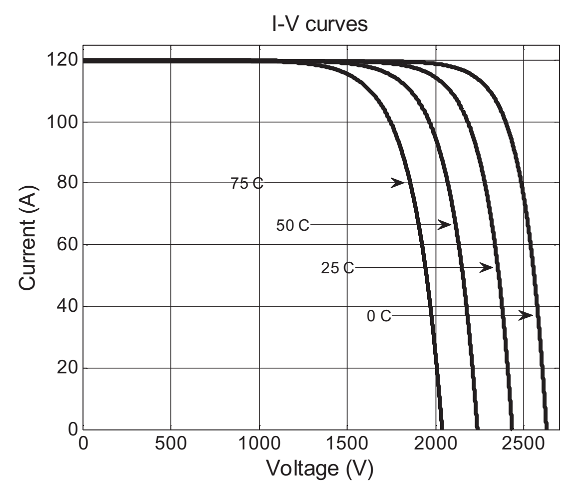


Fig. 12. *I–V* characteristics of PV array at different temperatures and constant irradiation of 1000 W/m^2.

of three series connected PV panels and each panel illuminated with different irradiation level, hence representing as a partially shaded PV array. Panel 1 is operating at 1000 W/m^2 25 °C, panel 2 at 800 W/m^2 25 °C, panel 3 at 300 W/m^2 25 °C. Figs. 13 and 14 show the *I–V* and *P–V* curve characteristics of array. *I–V* curve shows the multiple steps and *P–V* curve shows multiple peaks. Number of these steps/peaks depends upon the number of shaded pattern used. It can be seen from Fig. 13, at lower voltage level (from 0 to 49 V) only panel 1 is functioning and other two panels are bypassed through the bypass diodes and they do not take part in the

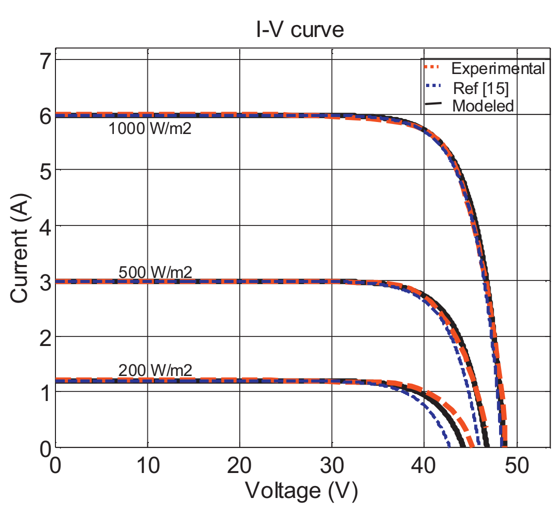


Fig. 10. Comparison between proposed PV model and Ref. [15].

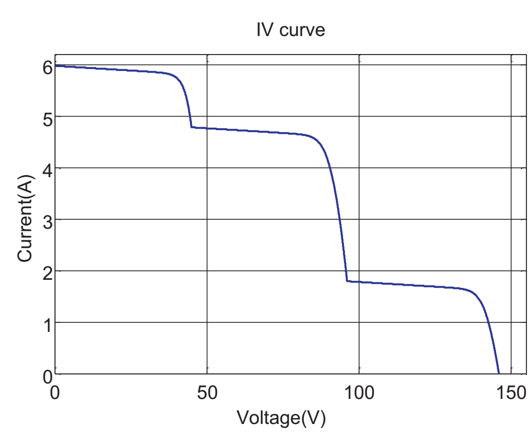


Fig. 13. *I–V* curve for partial shaded PV array.

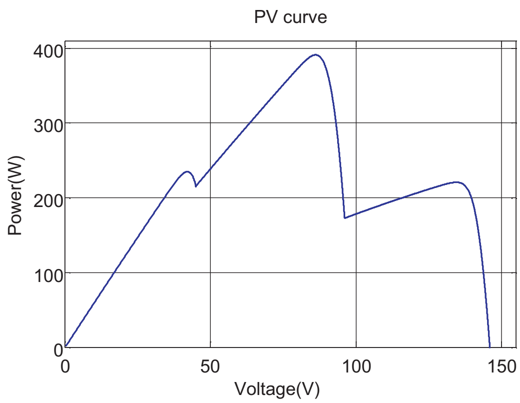


Fig. 14. *P–V* curve for partial shaded PV array.

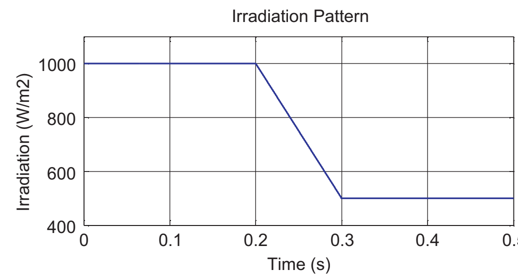


Fig. 16. Irradiation pattern used in test 3.

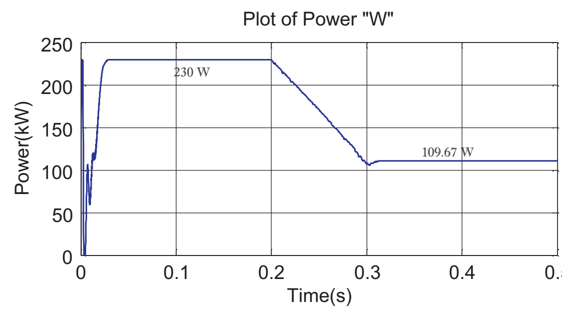


Fig. 17. Plot of PV panel power (PPV) vs time.

overall output voltage as the irradiation level of panel 1 is higher than other two panels. In the intermediate voltage level (from 49 to 98 V) panel 1 and panel 2 are operating and panel 3 is bypassed. From Fig. 13 it can be noticed that when panel 2 started working PV array current trim down abruptly to a lower value of 4.8 A. Reason for this drastic change is that the panel 2 is illuminated with lesser irradiation and it cannot produce more current than this value. Similarly, at high voltage level (greater than 98 V) all the three panels are functioning and the current is limited by panel 3 because it has the lowest irradiation level. This test verifies the robustness of the designed simulator under the harsh condition of partial shading.

4.4. *Test 4: performance with converter and MPPT controller*

This test shows the capability of a proposed simulator to work in conjunction with the power electronic devices and MPPT controller. Fig. 15 shows a complete PV system build in MATLAB/Simulink, consisting of PV simulator, DC–DC boost converter, MPPT controller, and a load. The PV simulator will generate voltage and current depending upon the ambient conditions (irradiation and temperature). The values of the current and voltage are varying due to changing atmospheric condition. Therefore, DC–DC boost converter is used to maintain the output constant and available for the load where MPPT works as a controller for the DC–DC converter.

A mc-Si PV panel is used in this test and its electrical data is given in the Table 2. A non-linear time domain simulation is carried out and a change in solar radiation is applied to assess the robustness of the proposed simulator in conjunction with converter and MPPT controller. Irradiation pattern is shown in Fig. 16. The solar radiation is decreased from 1000 (W/m^2) to 500 (W/m^2) between 0.2 s and 0.3 s. Fig. 17 demonstrates the output PV power and illustrates that the MPPT controller is tracking the maximum power from the PV panel. The results depict the dynamic performance of the overall system with the proposed simulator.

This test validates the operation of proposed PV simulator while interfacing it with power electronic converter and MPPT controller. It allows the user to study the behavior of the whole system under different operating conditions. Moreover, it can also be used to verify the effectiveness of MPPT controllers designed for normal and shaded conditions.

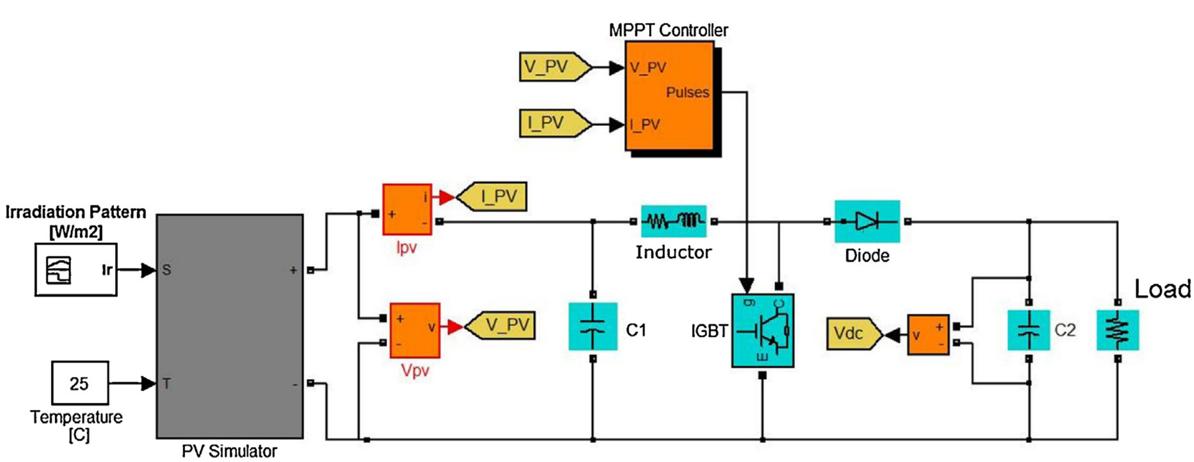


Fig. 15. PV system in Simulink.

5. Conclusion

In this paper, a comprehensive electrical modeling of PV has been carried out and a generalized PV simulator has been proposed and designed in MATLAB/Simulink software package. The proposed simulator has been developed as a masked block. It can simulate any number of panels connected in series and parallel. It has shown that the developed simulator can generate the real *I–V* and *P–V* curve of PV under different operating conditions including the harsh condition of partial shading. Further, the designed simulator can also be utilized in a complete PV system interfaced with different power electronic devices and MPPT controllers. Four different tests have been conducted and the results of these tests verify the effectiveness of the proposed simulator. It is envisaged that the developed PV array simulator can be very helpful for the PV design engineers in the simulation study prior to experimental verification.

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