

Vinod; Kumar, Raj; Singh, S. K.

## Article

# Solar photovoltaic modeling and simulation: As a renewable energy solution

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## Research paper

## Solar photovoltaic modeling and simulation: As a renewable energy solution

Vinod<sup>a,\*</sup>, Raj Kumar<sup>a</sup>, S.K. Singh<sup>b</sup><sup>a</sup> Department of Mechanical Engineering, D. C. R. U. S. T, Murthal 131039, Haryana, India<sup>b</sup> Department of Physics, D. C. R. U. S. T, Murthal 131039, Haryana, India

## HIGHLIGHTS

- Stepwise PV modeling, simulation and analysis play a major role to mount PV system.
- Maximum relative error is 1.65%, thus a good agreement was found among PV model and datasheet values.
- Modeling technique assist researchers and manufactures to understand the PV system.
- Modeling of PV module shows good results in real metrological conditions.
- It is presumed as a sturdy package and helps to boost solar PV manufacturing sector.

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## ABSTRACT

In renewable power generation, solar photovoltaic as clean and green energy technology plays a vital role to fulfill the power shortage of any country. Modeling, simulation and analysis of solar photovoltaic (PV) generator is a vital phase prior to mount PV system at any location, which helps to understand the behavior and characteristics in real climatic conditions of that location. In this context, a single diode equivalent circuit model with the stepwise detailed simulation of a solar PV module under Matlab/Simulink ambience is presented. I–V and P–V graph of solar PV module provide a broad understanding to researchers, manufacturers and social communities. The simulated result of the PV module is verified by the manufacturer data-sheet of JAP6-72-320/4BB module and maximum relative error percentage is found 1.65% which shows a good agreement between manufacturer values and simulated values. Moreover, the performance of PV module for real metrological data (irradiance and temperature) shows good results. In addition to this, it is presumed as a sturdy tool to evaluate the performance of any solar PV modules.

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## 1. Introduction

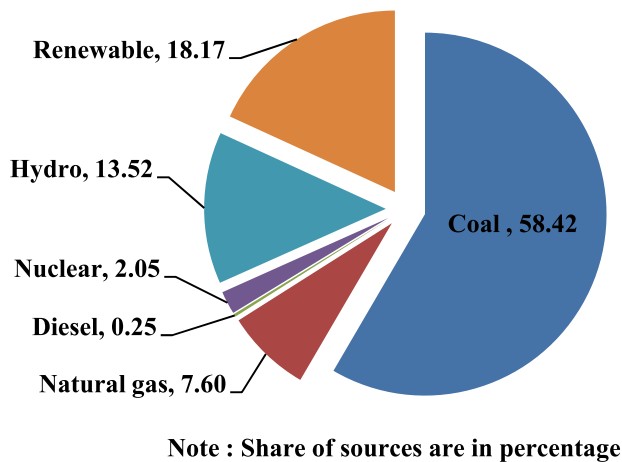
The economic development, industrial progress, societal growth, access to affordable and sustainable electric power is the fundamental requirement of any country. The demand for electricity in India is growing continuously, due to the industrialization and urbanization (Kanchan and Kumarankandath, 2015). Being a growing country, India's total installed power capacity addition comes from different sources is 1.362 GW in 1947 to 326.849 GW up to 31st March 2017 (Central Electricity Authority, 2017a). No doubt, coal/lignite based power supply in India is a dominant source of electricity since independence. These conventional power generators are responsible for large numbers of human mortality due to spewing of the huge amount of pollutant gases and heavy metals from the stack (Shahzad Baig and Yousaf, 2017; Geonka and Guttikunda, 2012). Fig. 1 depicts the sources of all

India installed capacity of electricity in percentage. India's total installed generating capacity of power is 331.117 GW as on 31st Oct 2017, from this thermal share is 66.27%, renewable energy is 18.17%, nuclear holds 2.05% and contribution of hydro energy is 13.52% (Central Electricity Authority, 2017b). In Indian electricity system, the main source of energy supply is coal-based power with 58.42% share. Thus coal forms the main constituent of electricity since independence.

The dependency on the conventional source of energy may be reduced by hybridization of various renewable energy sources along with energy storage technologies which play a critical role to tackle the power uncertainties (Hemmati and Saboori, 2016). In the present scenario, power distribution system of any country considered the energy storage as a key element (Saboori et al., 2017). It is because this can improve grid stability, increase system efficiency, enhance renewable energy penetration, help to mitigate environmental and health implications by conserving fossil fuels (Amrouche et al., 2016; Aneke and Wang, 2016). Also, the operational cost of power distribution network can be reduced by

\* Corresponding author.

E-mail address: [vinodnandal18@gmail.com](mailto:vinodnandal18@gmail.com) (Vinod).



**Fig. 1.** Source wise all India installed capacity of electricity.  
Source: Central Electricity Authority (2017b).

**Table 1**  
Renewable energy installed capacity.  
Source: Central Electricity Authority (2017b).

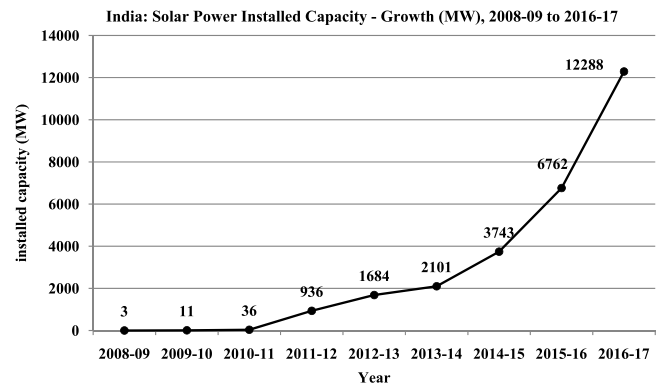
Renewable energy sources	Installation capacity (MW)	Share (%)
Small hydro power	4389.55	7.29
Wind power	32700.64	54.35
Bio-power	8295.78	13.79
Solar power	14771.69	24.55
<b>Total</b>	<b>60 157.66</b>	<b>100</b>

adoption of battery energy storage system technology (Hemmati, 2018). Thus blend of solar energy and energy storage technologies boost rural energy access, which ultimately increase the economic growth of any country (Kim and Jung, 2018).

### 1.1. India's renewable energy potential

In order to access affordable and environmentally green power to the citizens of India by March 2019, the Indian government has launched a drafted scheme named “24X7 Power for All” (Ministry of New and Renewable Energy (MNRE), 2017). To fulfill the power requirement of India, renewable energy will provide a sustainable solution as a green and pollution free power for the development of India. This will also help in achieving the target of “Paris Agreement” on climate change, under this by 2030 Indian government ensures that at least 40% of its power to be generated from renewable sources (Gould, 2015). The total installed capacity of renewable energy from different sources is 60.157 GW as on 30th September 2017 as shown in Table 1 (Central Electricity Authority, 2017b).

The Indian government has set an ambitious goal of generating 175 GW of polluting free power by 2022. The estimated potential of renewable energy in India is approximately 900 GW from diverse resources, such as from small hydro—20 GW; wind power—102 GW (80 meter mast height), biomass energy—25 GW and solar power is 750 GW, considering 3% wasteland in the country (Ministry of New and Renewable Energy (MNRE), 2017). Thus from above facts, solar power has emerged as a major source of green power among renewable energy, which will create history for the development of the country and achieve new heights in Indian power sector.



**Fig. 2.** Development of solar energy in India.  
Source: (a) Central Electricity Authority (2017b), (b) Ministry of New and Renewable Energy (MNRE) (2017).

### 1.2. Harnessing solar energy in Indian context

Demographic of the nation make India as a tropical country with good intensity radiation and excellent solar energy potential. In a year the average solar radiation fall is 4–7 kWh/m<sup>2</sup> with 300 sunny days (Kirmani et al., 2015). The prime minister of India revised the goal of 20 GW solar energy into 100 GW aspiring mission of solar energy installation by 2022 (Nathan, 2014). The total installed capacity of solar power is only 12.28 GW as on 31.03.2017, this shows that India has a huge untapped potential for harvesting solar energy with no carbon emissions. Fig. 2 illustrates the development in installed capacity of solar power from the year 2008 to 2017. It begins from 3 MW in the year 2008–09 and has risen up to 12288.83 MW by the end of the financial year 2017 (Central Electricity Authority, 2017a; Ministry of New and Renewable Energy (MNRE), 2017). Thus India has looked upward in the accomplishment of solar power capacity addition since 2008.

Power generating capacity of India is anticipated to rise 746 GW, by 2030 (Gould, 2015). Demographic of the nation make India as a solar power abundant country and the estimated potential is about 750 GW (Ministry of New and Renewable Energy (MNRE), 2017). Therefore, solar energy will harness the overall energy requirement of the country.

### 1.3. Literature review

In renewable power generation, solar photovoltaic as clean and green energy technology plays a vital role to fulfill the power shortage of the country. During the last decade, various studies have been piloted by several researchers for modeling of photovoltaic technology with various procedures and evaluate the number of parameters using the variety of simulation software's, Amrani and Rekioua (2006), Rekioua and Matagne (2012) and Pendem and Mikkili (2018).

Adamo et al. (2011) prepared IP10P solar PV model by developing PV panel evaluation tools based on Matlab and Labview software to calculate and monitor the modeling parameters and assess the model under summer outdoor environment. Banu and Istrate (2012) prepared solar PV module I–V and P–V characteristics using empirical data and curve fitting tool. The limitation of this technique is that it is unable to gather enough data if no experimental setup is provided. Therefore it is difficult to develop and modeled characteristics curves. Rekioua and Matagne (2012) illustrated various PV models modeling using Matlab/Simulink application. These models reveal the operational and behavioral

characteristics of PV generators and also analyzed the experimental results with the simulation outcomes thoroughly. Patel and Sharma (2013) and Krismadinata et al. (2013) presented the circuit based solar PV model in Matlab and simulated the same for different values of radiation and temperature. These papers only described the final model but lack in detailed modeling of a sub-system of final solar PV model. Mohammedi et al. (2013) described the PV models mathematically to evaluate the various model parameters accurately, along with this compare the experimental and simulated outcomes of PV models thoroughly. Authors also developed and evaluate the performance of photovoltaic driven water pumping system. Rahman et al. (2014) developed a model of polycrystalline PV module supplied by the National Institute of Standards and Technology to evaluate the output power against the measured output power of the module. Yatimi and Aroudam (2015) presented the mathematical modeling of solar PV module in Matlab environment and simulated the model in real climatic conditions of Tetouan-Northern Morocco but unfortunately, in this paper authors do not describe the detailed modeling of PV model. Yildiran and Tacer (2016) developed the solar PV model using the basic governing equations in Matlab/Simulink and compared the simulated results with the manufacturer data results very well but detailed stepwise modeling of PV module is not presented in this research. In the work of Abdullahi et al. (2017), modeling of monocrystalline PV module is prepared under Matlab/Simulink ambience and compared the simulated and measured outdoor results very well but lacks in presenting the stepwise development of PV modeling. Mendalek and Al-Haddad (2017) developed the PV module script in Matlab using the mathematical governing equation and identified the model parameters of commercial PV module KC200GT and simulate the model for various irradiation and temperature values. AbdelHady (2017) and Fara and Craciunescu (2017) proposed the Matlab/Simulink model of PV module and identified the characteristics curve by varying irradiation and temperature conditions. Pendem and Mikkili (2018) presented the modeling and simulation of KC200GT PV module in Matlab/Simulink application and simultaneously author described the partial shading effect on PV module characteristic in detail, but phase wise development of PV module modeling is not described, so readers face difficulties to simulate and understand the model. By observing above investigations, there is vast scope in modeling simulation and analysis of photovoltaic module.

In view of the never-ending impact of solar energy to the social development of any country, it is truly saying that solar power is a leading prospective solution for power shortage (Sindhu et al., 2016). It is essential to understand how achievable it is with the given recourses and infrastructure. There are certain hindrances for proper implementation of solar energy in the country viz. Lack of assessment of solar resource data, needs of user-friendly computation and simulation tools to analyze solar generator system, computation for appropriate sizing of photovoltaic system etc. (Fara and Craciunescu, 2017). So to overcome the hindrance and to understand the real system behavior we require software packages for authentication of the model. There are lots of software packages are exists in the area of modeling, simulation and analysis of PV system viz. Solar Pro, PV-Design Pro, PV-Spice, PV CAD, but they have some disadvantages like very expensive software, only commercially available package, interfacing problem with electronic power system and proprietary available packages (Fara and Craciunescu, 2017; Sharma et al., 2014). To fulfill the above drawbacks Matlab/Simulink package can be used, these packages is user-friendly, flexible, develops an accurate model, simulate the complex model, and provides lots of applications in power electronics, solar PV system and other engineering disciplines. This package is easily available in academic, industrial and research labs (Fara and Craciunescu, 2017; Pandiarajan and Muthu, 2011; Qi and Ming, 2012).

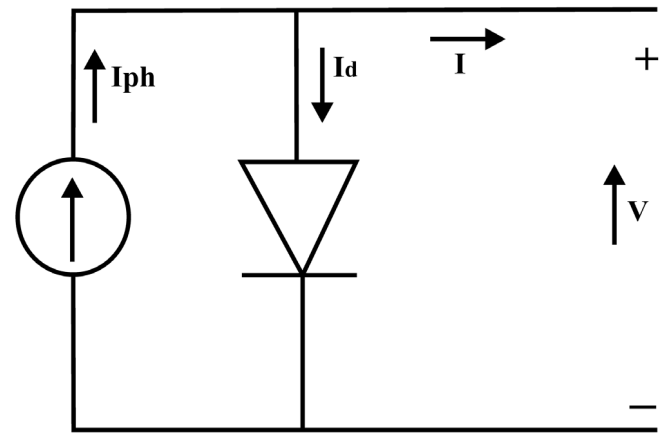


Fig. 3. Simplified equivalent circuit of PV panel.

Modeling, simulation and analysis of solar PV generator is a vital phase prior to mount PV system at any location, which helps in understanding the real behavior and characteristics in real climatic conditions of that location (Meflah et al., 2017). During the last decade, severely researchers investigated modeling and simulation of solar PV modules to obtain the informative results. There are various methods of modeling and optimization of solar PV modules like analytical methods, linearization methods, artificial intelligence methods, numerical methods, artificial neural networks, fuzzy methods and genetic algorithms etc. (Lyden et al., 2012; Rekioua and Matagne, 2012). In the next section modeling and simulation of PV model is discussed.

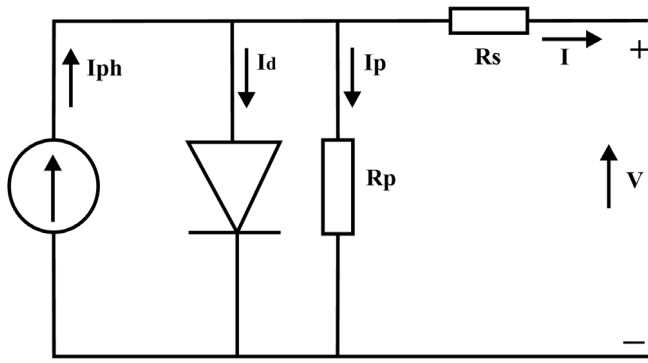
## 2. Methodology for solar PV module

In this research simplified, an accurate and mathematical model of single diode equivalent photo-generator module was developed using analytical methods under Matlab/Simulink environment. For the development of solar PV module stepwise approach of modeling and simulation is adopted and manufacture data of JAP6-72-320/4BB solar PV module is considered during modeling (Datasheet JAP6-72-320/4BB, JA Solar). This can easily evaluate the characteristics of solar PV cell/module. To validate the model manufacture data sheet results and simulated results are compared.

## 3. Mathematical formulation of solar PV module

A solar cell is a fundamental device for conversion of photon energy into pollution-free electricity if this device is connected in series and parallel fashion than PV module is formed. Further to build PV arrays these modules are coupled in series and parallel arrangement which are responsible to generate clean and green electricity. A single solar cell can be represented as a component of an electrical circuit. It contains a p–n junction called as a diode, a photocurrent generator represented a generation of current from light and two resistors, one is arranged in series and another one is in parallel which described the Joule effect and recombination losses. Then this combination is called as a single diode solar cell model (Rekioua and Matagne, 2012; Rahman et al., 2014; Mohammedi et al., 2013; Yildiran and Tacer, 2016; Fara and Craciunescu, 2017; Pendem and Mikkili, 2018; Altas and Sharaf, 2007; Villalva et al., 2009). For modeling of a solar PV module same methodology is adopted as described for a solar cell. The simplified circuit model of a solar panel is illustrated in Fig. 3.





**Fig. 4.** Equivalent circuit of real model for PV panel.  
Source: (a) Mendalek and Al-Haddad (2017), (b) Aoun et al. (2014).

### 3.1. Mathematical modeling of ideal solar cell

The solar PV device can be represented as an ideal solar cell with a current source ( $I_{ph}$ ) parallel to the diode as illustrated in Fig. 3 and by using the Kirchhoff's first law the output current of an ideal solar cell is described in Eq. (1).

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

From the theory of semiconductors the fundamental mathematical equation that describes the I–V characteristics of the PV solar cell known as Shockley's diode current equation as illustrated in Eq. (2) (Sera et al., 2007; Bellini et al., 2009).

$$I_d = I_s \left[ \exp \left( \frac{qV_{oc}}{N_s K A T_o} \right) - 1 \right] \quad (2)$$

By putting value of the  $I_d$  in Eq. (1) produces the output current  $I$  of an ideal solar cell as described in Eq. (3).

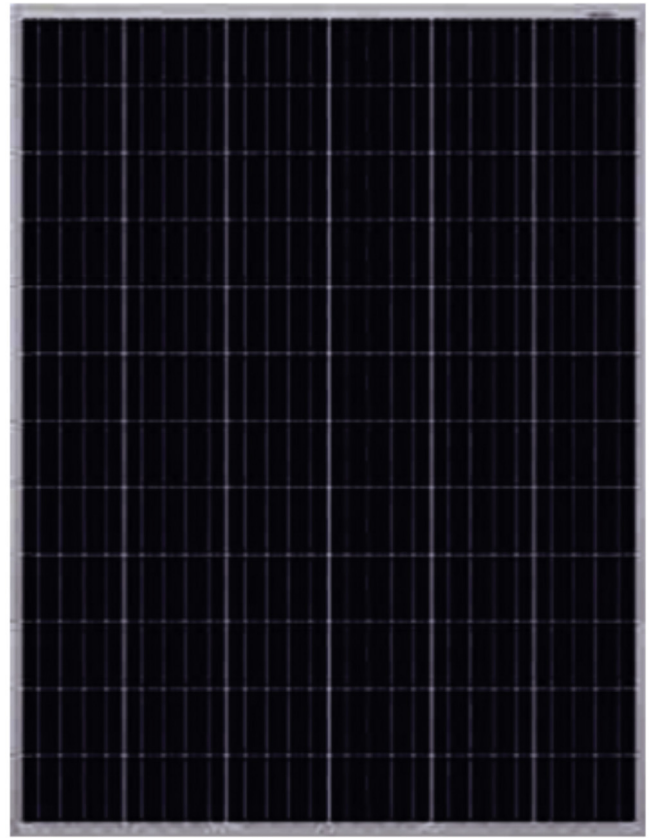
$$I = I_{ph} - I_s \left[ \exp \left( \frac{qV_{oc}}{N_s K A T_o} \right) - 1 \right] \quad (3)$$

In ideal case solar cell provides a very good approximation to photon generated current which is directly proportional to illumination intensity and irradiance. There are some parameters which are not taken into consideration in ideal case model and that actually affect the output of a PV device in real or practical cases (Bellini et al., 2009; Villalva et al., 2009; Sera et al., 2007). In the next subsection here presents the single diode modified model for the real case.

### 3.2. Mathematical model of a PV cell (real/practical cell case)

A more realistic circuit model of solar PV cell is illustrated in Fig. 4. This is also identified as real single diode model with series resistance ( $R_s$ ) and parallel resistance ( $R_p$ ). Ideally  $R_s$  and  $R_p$  are ignored but in reality it is not possible to overlook these resistances, because efficiency of the PV solar cell is affected by these parameters (Villalva et al., 2009; Pandiarajan and Muthu, 2011; Rekioua and Matagne, 2012; Lyden et al., 2012; Mohammadi et al., 2013; Sera et al., 2007). So the appropriate model is represented in Fig. 4.

$R_s$ , is series resistance in the current path and considered as losses by Joule effect, it is primarily due to metal grids, semiconductor materials, collecting bus and its connections.  $R_p$ , is parallel resistances, it is associated with seepage of current due to the cell thickness, surface effects and called as shunt resistance. The effect of  $R_s$  is prominent due to the multiplication of cells resistance in the PV module as compared to  $R_p$ . The effect of  $R_p$  is only



**Fig. 5.** Solar PV module of JAP6-72-320/4BB.  
Source: Datasheet JAP6-72-320/4BB, JA solar.

conspicuous when large numbers of PV modules are considered in the solar photovoltaic system (Bellini et al., 2009; Villalva et al., 2009; Qi and Ming, 2012; Lyden et al., 2012; Sera et al., 2007). So,  $R_s$  is taken into consideration and  $R_p$  is considered to be infinite then diode current Eq. (2) is modified to Eq. (4).

$$I_d = I_s \left[ \exp \left( \frac{q(V + IR_s)}{N_s K A T_o} \right) - 1 \right] \quad (4)$$

When  $R_s$  was taken into account, which modifies Eq. (3) and governed Eq. (5).

$$I = I_{ph} - I_s \left[ \exp \left( \frac{q(V + IR_s)}{N_s K A T_o} \right) - 1 \right] \quad (5)$$

Considering the PV cells coupled in a series–parallel manner and the output current  $I$  is computed than Eq. (5) can be modified and illustrated in Eq. (6) as follows:

$$I = N_p * I_{ph} - N_p * I_s \left[ \exp \left( \frac{q(V + IR_s)}{N_s K A T_o} \right) - 1 \right] \quad (6)$$

Considering the above-mentioned equations for PV cell modeling, there are some parameters that need to be determined for modeling, which depends on the selected model of PV module (Bellini et al., 2009). In this model we require to compute  $I_{ph}$ ,  $I_{rs}$ ,  $I_s$ , and this is obtained from following equations.  $I_{ph}$  Photocurrent is proportional to the incident flux and independent to  $V$  (or  $R_s$ ), it is linearly dependent on the solar radiation and also influenced by temperature according to the following equation of  $I_{ph}$  illustrated in Eq. (7).

$$I_{ph} = [I_{sc} + K_i (T_o - T_r)] * \frac{G}{G_{ref}} \quad (7)$$

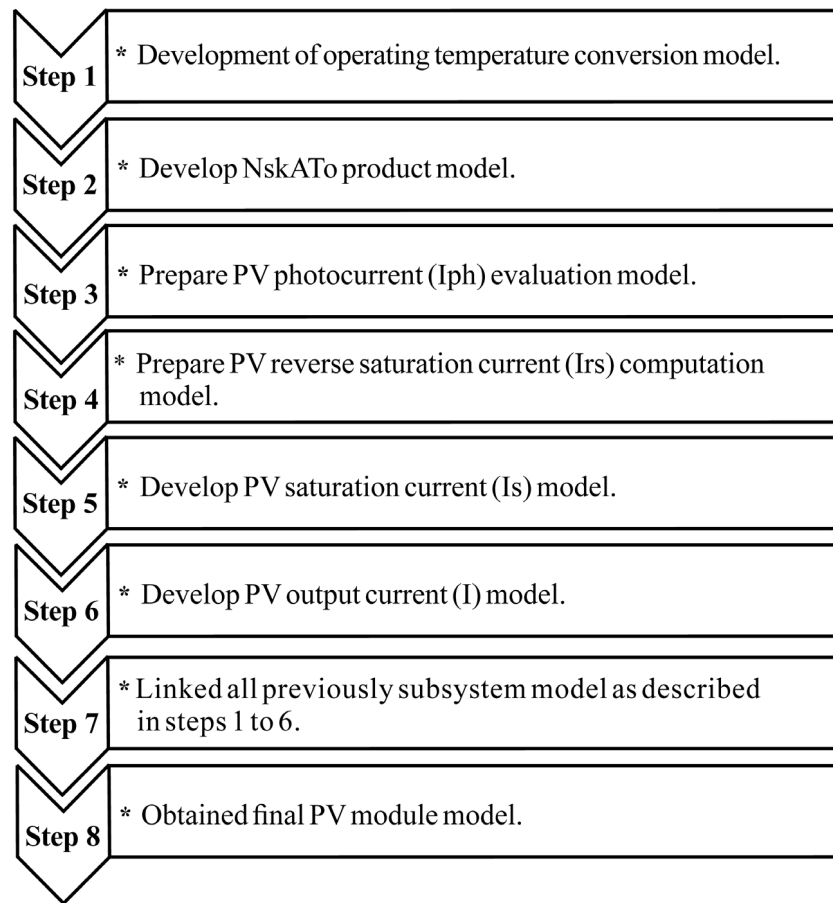


Fig. 6. Photovoltaic modeling steps involved in Simulink.

Reverse saturation current  $I_{rs}$  and Saturation current  $I_s$  is calculated by using Eqs. (8) and (9).

$$I_{rs} = I_{sc} / \left[ \exp \left( \frac{qV_{oc}}{N_s K A T_o} \right) - 1 \right] \quad (8)$$

$$I_s = I_{rs} [T_o/T_r]^3 \exp \left[ \left( \frac{qE_g}{AK} \right) \left( \frac{1}{T_r} - \frac{1}{T_o} \right) \right] \quad (9)$$

The ideality factor  $A$  and energy band gap  $E_g$  obtained from the selected model, which is taken from the manufacturer of the selected module.

### 3.3. Reference model for modeling

In order to develop the modeling and carry out the simulation of a solar panel model, the JAP6-72-320/4BB solar PV module has been selected and depicted in Fig. 5.

The module consists of 72 polycrystalline silicon solar cells connected in series. This module reduces the series resistance between cells due to back to back cell interconnectors, which offer high conversion efficiency and the key specifications are illustrated in Table 2.

## 4. Simulation model

The mathematical model of solar PV module which is based on the fundamental building blocks of the current source, diode, series and parallel resistors is developed in step by step procedure under Matlab/Simulink system using the above-described modeling Eqs. (1)–(9). Fig. 6 depicts the steps involved in PV modeling. The desired PV model is equipped with subsystems and these

Table 2

Electrical parameters of JAP6-72-320/4BB solar PV module.  
Source: Data sheet JAP6-72-320/4BB, JA solar.

S. No.	Parameters	Variables	Values
1.	Maximum power at STC (Pm)	Pm	320 W
2.	Maximum power voltage (Vmp)	Vm	37.38 V
3.	Maximum power current (Imp)	Im	8.56 A
4.	Open circuit voltage ( $V_{oc}$ )	$V_{oc}$	46.22 V
5.	Short-circuit current ( $I_{sc}$ )	$I_{sc}$	9.06 A
6.	Total series cells	$N_s$	72
7.	Total parallel cells	$N_p$	1
8.	Ideality factor of diode	$A$	1.3
9.	Cell short circuit current temperature coefficient of $I_{sc}$	$K_i$	0.058%/°C
10.	Reference temperature	$T_{ref}$	25 °C
11.	Solar Irradiance	$G_{ref}$	1000 at STC

subsystems are developed and connected to each other (Kharb et al., 2013; Rekioua and Matagne, 2012; Meflah et al., 2017; Pendem and Mikkili, 2018). For simulation JAP6-72-320/4BB PV solar module has selected as a reference model and provides input parameters for modeling (Datasheet JAP6-72-320/4BB, JA Solar). The final model of PV cell transforms the solar energy into electricity and provides the characteristics curves for given radiation and temperature as input parameters.

### Step 1: Operating temperature conversion model

In solar PV system, temperature act as an input parameter in degree Celsius but for development of PV modeling the temperature used in the mathematical formulations is in Kelvin (Hamdi, 2017; Dewagan et al., 2015), so all the temperature values need

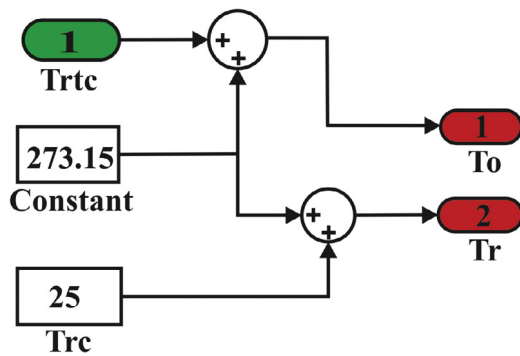


Fig. 7. Operating temperature conversion model.

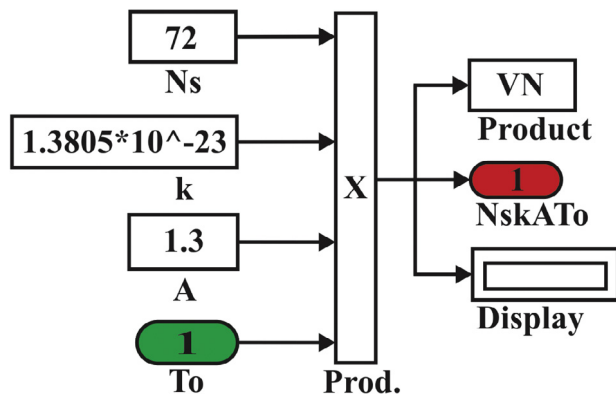


Fig. 8. Product model of NskATo.

to be calculated in Kelvin which is depicted in Fig. 7 and act as a subsystem for solar PV modeling.

### Step 2: Product model

During the mathematical modeling of PV Module as described in the previous section shows the NskATo in Eqs. (3) to (8), which takes operating temperature in Kelvin. Therefore a product model of NskATo is developed in Simulink to calculate the value and use

as a subsystem in final PV model (Kharb et al., 2013; Salem, 2014). Fig. 8 shows the product model.

### Step 3: PV photocurrent model

Model of PV photocurrent act as a subsystem in solar PV modeling which is developed using Eq. (7) in Simulink. The photocurrent behaves linearly on the solar irradiance and is also influenced by the operating temperature (Rekioua and Matagne, 2012; Meflah et al., 2017). The detailed implementation of Iph in Simulink environment, with its subsystem and effect of environmental factor solar irradiance (G) and temperature (To) as input parameters is illustrated in Fig. 9.

### Step 4: PV reverse saturation current mode

In Fig. 10 reverse saturation current model is developed by using Eq. (8) in the Simulink environment. Also, manufacture data sheet parameters are utilized to develop the model (Pandiarajan and Muthu, 2011; Meflah et al., 2017).

### Step 5: PV saturation current model

Eq. (9) represents saturation current (Is), which varies with the cell temperature and the model for same is prepared in the Simulink environment. The reverse saturation current subsystem model as shown in Fig. 10 is used as inputs along with energy band-gap, electron charge, reference temperature and operating temperature of module (Kharb et al., 2013; Abdulkadir et al., 2012). The simulation model is shown in Fig. 11 and evaluates the saturation current.

### Step 6: PV output current model

Output current given by Eq. (6) is developed in Simulink as illustrated in Fig. 12. The output current can be investigated with respect to the voltage which is dependent on irradiance and temperature using this Simulink model.

### Step 7: Linked model

The entire subsystem model developed during step 1 to step 6 in the Simulink environment connected all together and formed a linked model as shown in Fig. 13.

### Step 8: Final PV module model

As illustrated in Fig. 14 the final PV solar module model is developed in the Simulink environment, which consists of irradiance (G) and temperature (To) as the input parameters and provides output results as current (I) and voltage (V).

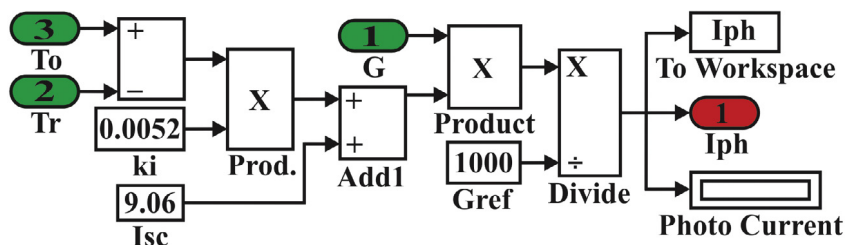


Fig. 9. Photocurrent model.

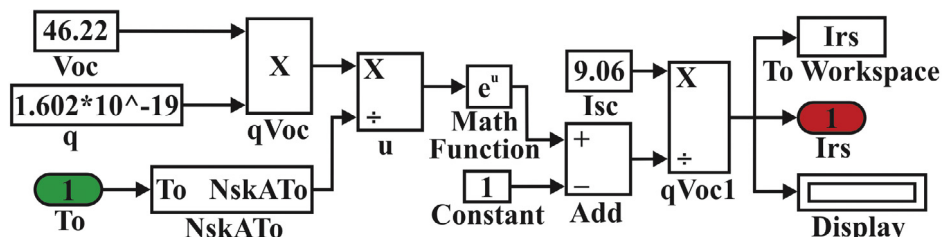
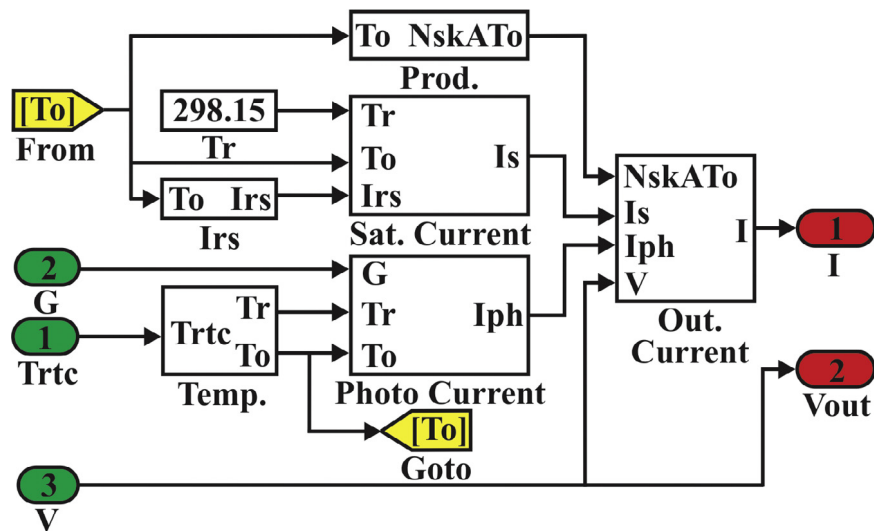
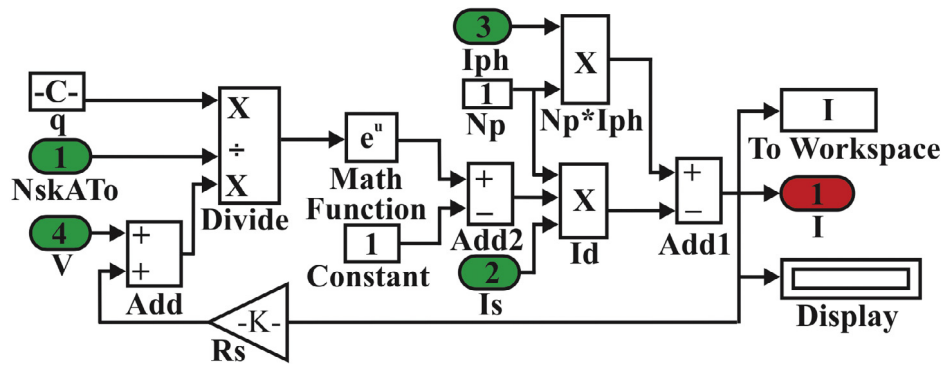
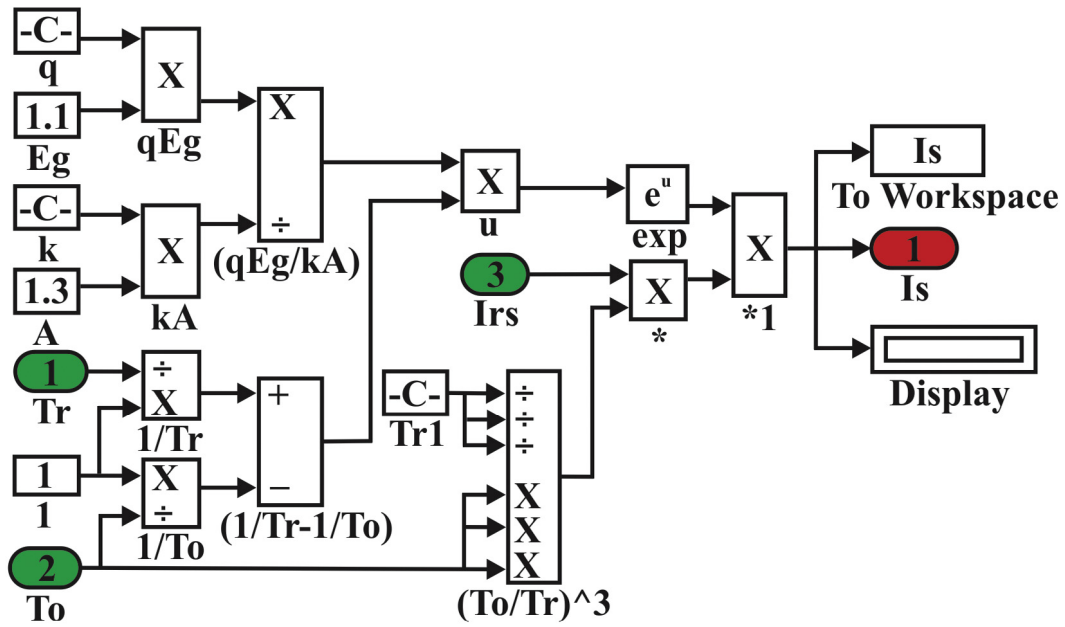


Fig. 10. Reverse saturation current model.





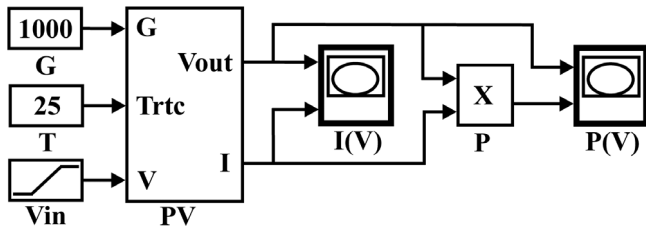


Fig. 14. Final PV module model.

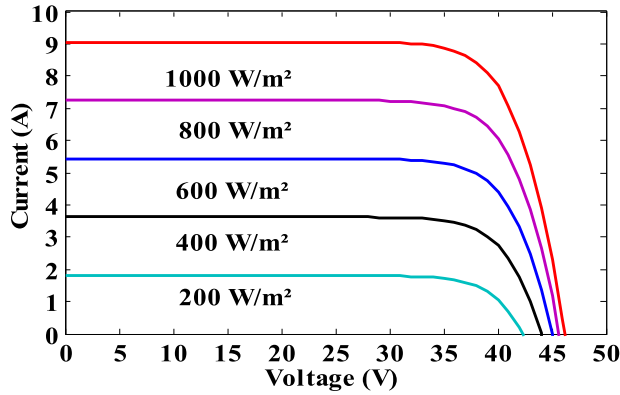


Fig. 15. I-V characteristics, varying irradiance at constant temperature.

Table 3

Comparison of reference model values and simulation model values at STC.

Parameters	Parameters of JAP6-72/320/4BB datasheet - reference model	Parameters from simulation of the model	Relative error (%)
Pmax (W)	320	319.9996	0.000125
Voc (V)	46.22	46.2063	0.030
Isc (A)	9.06	9.06	0
Vmp (V)	37.38	38	1.63
Imp (A)	8.56	8.421	1.65
Efficiency ( $\eta$ %)	16.51	16.51	0

## 5. Simulation results and discussion

Solar PV module model is developed under Matlab/Simulink environment by using the previously discussed mathematical equations of solar cells. The JAP6-72/320/4BB module parameters from manufacturer datasheet are incorporated during simulation block model and consider as reference module. The final Solar PV model as depicted in Fig. 14 are simulated and obtained output results as current, voltage and power, due to the variation of radiation and temperature as input parameters (Adamo et al., 2011; Rekioua and Matagne, 2012).

### 5.1. Evaluation of model in standard test conditions

The final PV solar model is evaluated in standard test conditions (STC). These conditions are kept same in all over the world and performed in irradiance of  $1000 \text{ W/m}^2$  under a temperature of  $25^\circ\text{C}$  in air mass of 1.5 (Abdullahi et al., 2017). Simulation of the solar PV model executes the I-V and P-V characteristics curves. Generally a good agreement was observed between various performance parameters results of reference model and simulated PV model at STC as illustrated in Table 3. The relative error for all the parameters of solar PV model is comprised between 0 to 1.65%.

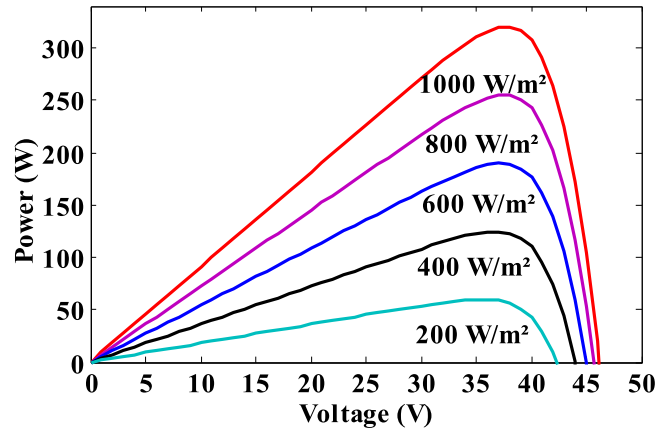


Fig. 16. P-V characteristics, varying solar radiation at constant temperature.

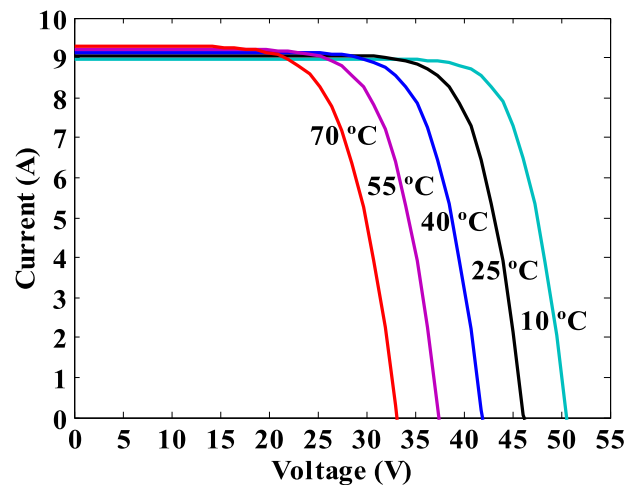


Fig. 17. I-V characteristics, varying temperature at constant solar radiation.

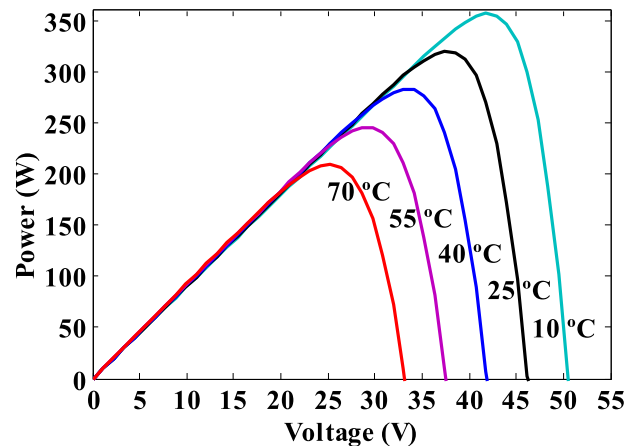


Fig. 18. P-V characteristics, varying temperature at constant solar radiation.

#### 5.1.1. Irradiance effects on PV solar module

The effect on solar PV model I-V and P-V characteristics curves is depicted in Figs. 15 and 16 by varying the intensity of irradiance from  $200 \text{ W/m}^2$  to  $1000 \text{ W/m}^2$  at constant temperature of  $25^\circ\text{C}$ . It is observed that current remains constant with rising voltage up to 30 V after which it decreases. Moreover, the current increases

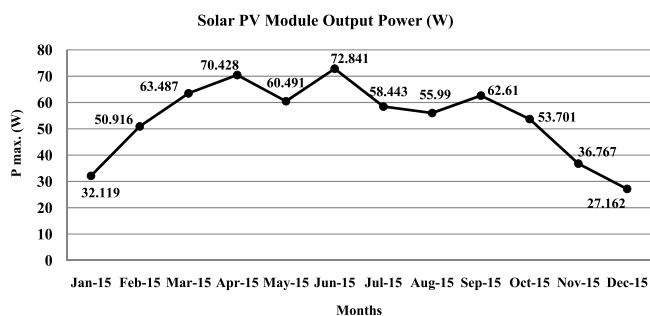


Fig. 19. Solar PV module output power ( $P_{max}$ ), month wise.

while rising the irradiance intensity. This demonstrates that irradiance has a substantial effect on short circuit current, at the same time open circuit voltage is quite low as shown in Fig. 15. The maximum power evidence exists on power performance curves. The generation of power by solar PV model is increased by increasing the intensity of solar irradiance as shown in Fig. 16.

### 5.1.2. Temperature effect on PV solar module

The temperature demonstrates a significant effect on the output performance curves of PV solar module when irradiance intensity is kept constant at  $1000 \text{ W/m}^2$ . In current a minor variation is observed when the temperature varies from  $10^\circ\text{C}$  to  $70^\circ\text{C}$ . The voltage shows increasing trend in I–V performance curve when the atmospheric temperature reduces as illustrated in Fig. 17. Also, the solar cell generates more power, when the atmospheric temperature reduces as described in Fig. 18. Thus solar cell shows inverse relationship with temperature.

### 5.2. Solar PV model validation

The accuracy of the solar PV model is investigated by evaluating percentage relative error (RE) between the simulated results and the manufacturer datasheet results under STC conditions. Table 3 shows the relative error percentage and found below 1.70% for all the parameters. A good agreement was observed between manufacturer data specifications and simulated PV solar model results. The relative error was observed below 2% for all the parameters between the simulated solar PV model and the manufacturer specifications (Meflah et al., 2017). The relative error of maximum power output for different fifteen types of PV connections was found from 0.1% to 6.76% (Hashim and Khazaal, 2017). The error among modeling of PV module results and manufacturer datasheet

Table 4

Demographic position of SRRA, Murthal, Sonipat, Haryana-India.

Site name	SRRA (ID-2389), DCRUST, Murthal
District	Sonipat
State	Haryana
Latitude	$29^\circ 1' 40.9'' \text{ N}$
Longitude	$77^\circ 3' 28'' \text{ E}$
Elevation	213 m amsl.

Table 5

Solar PV model output parameter under real metrological data of the year 2015.

Months	Input parameters		Output parameters		
	Avg. value of $G (\text{W/m}^2)$	Avg. value of Amb. T ( $^\circ\text{C}$ )	Imp (A)	Vmp (V)	$P_{max}$ (W)
January	99.52	11.45	0.845	38.001	32.119
February	160.92	17.09	1.376	37.002	50.916
March	203.17	20.22	1.716	36.997	63.487
April	236.31	26.85	2.012	35.003	70.428
May	214.99	32.68	1.833	33.001	60.491
June	250.65	30.08	2.187	33.300	72.841
July	203.28	29.96	1.719	34.018	58.443
August	193.55	28.92	1.647	33.995	55.990
September	215.01	28.79	1.842	33.990	62.610
October	181.58	25.99	1.534	35.007	53.701
November	122.02	20.97	1.021	36.010	36.767
December	87.22	14.84	0.734	37.005	27.162

results was found less than 10% (Abdullahi et al., 2017). Thus simulation found good agreement for the characteristics curve and performance of the PV solar module.

### 5.3. Evaluation and findings of solar PV module in real metrological data

The performance of solar PV module has been determined in Matlab/Simulink by using the monthly average values of irradiance and ambient temperature of the year 2015 for the demographic location of Solar Radiation Resource Assessment (SRRA) center of Deenbandhu Chhotu Ram University of Science and Technology, Murthal (Station ID: 2389), Sonipat, Haryana, which was established by Ministry of New and Renewable Energy (MNRE) under Govt. of India. Table 4 shows the demographic position of SRRA, Murthal station, Haryana, India.

The output values of the solar PV model are shown in Table 5 using the monthly average values of irradiance ( $G$ ) and temperature ( $T$ ) as input parameters from January to December 2015. Here the irradiance changes from minimum  $87.22 \text{ W/m}^2$  to maximum

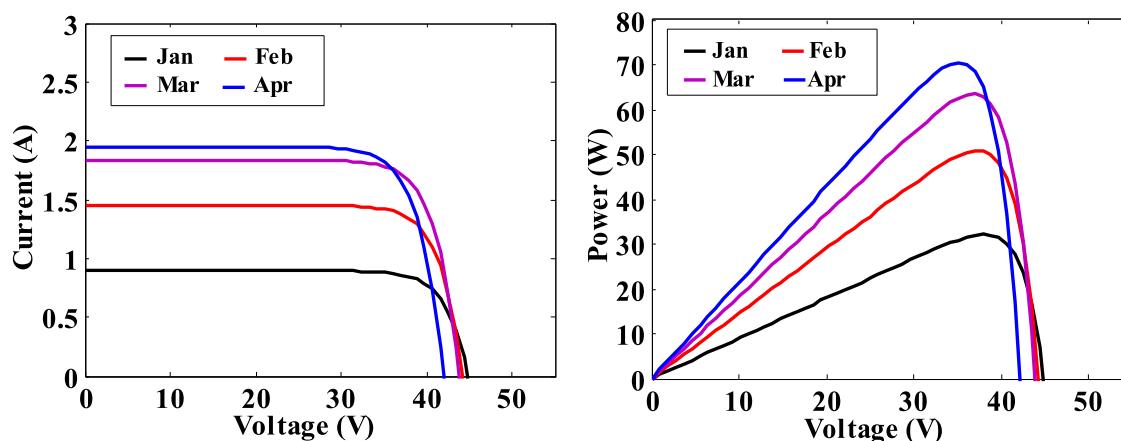


Fig. 20. I–V and P–V graphs for the month of Jan-15 to April-15.

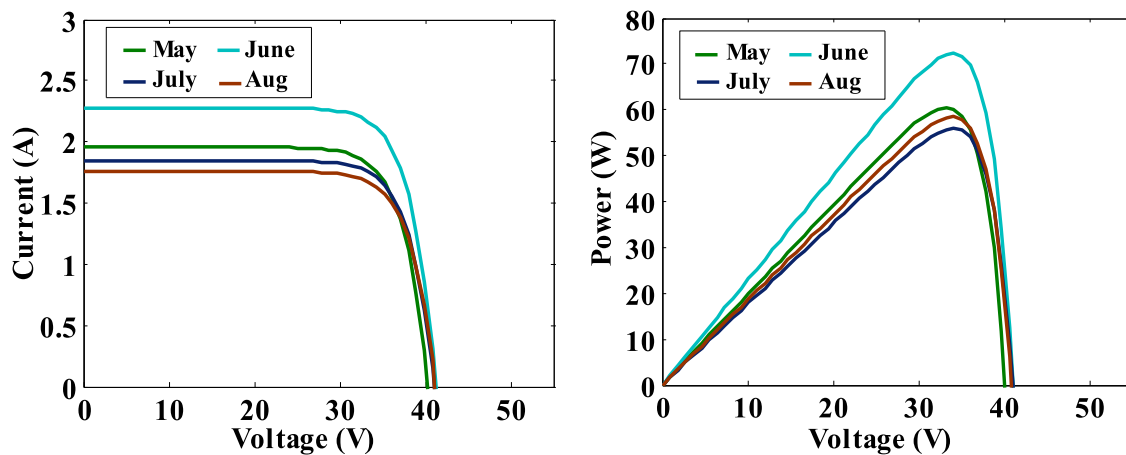


Fig. 21. I–V and P–V graphs for the month of May-15 to August-15.

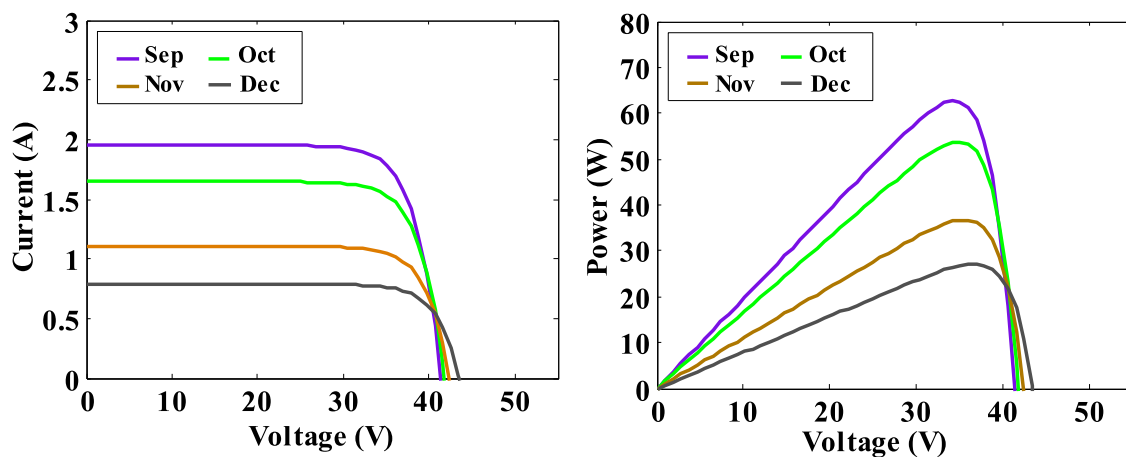


Fig. 22. I–V and P–V graphs for the month of September-15 to December-15.

250.65 W/m<sup>2</sup> and temperature varies from minimum 11.45 °C to maximum 32.68 °C.

I–V and P–V graphs of January to December 2015 values are simulated for solar PV model and illustrated in Figs. 20–22. A good consistency can be seen for all the important points of current, voltage and power when the irradiance and temperature varies for solar PV model. A good correlation is found between current and irradiance intensity, whenever the irradiance increases the current of solar PV model also increases as revealed in Figs. 20–22.

The minimum output power is 27.162 W in the month of December 2015 and maximum output power is 72.841 W in the month of June 2015 as depicted in Fig. 19. A good agreement was found in power output when the irradiance intensity increases from January to June. A drop in power output is also observed in the month of May, it is due to the decrease of irradiance intensity and also due to the maximum average temperature recorded in this month. It is observed that there is decrease in power output from July to December. It is also revealed that in the month of September there is rise in power output, it is due to the increase in irradiance intensity. This shows that when the irradiance increases, the output current are increased due to this the power of solar PV module is also increased.

## 6. Conclusions

An accurate single diode equivalent circuit model of PV solar module is described in this work. A stepwise method for simulating

a PV solar module under Matlab/Simulink ambience is outlined. This modeling technique assists researchers, manufactures and people to understand the operating performance curves of PV solar module easily. The maximum relative error percentage is found 1.65% which shows a good agreement between manufacturer values and simulated values. This verifies that simulation concur the characteristic curve and performance of the PV solar module. The performance of PV solar module for February to October metrological data (irradiance and temperature) provides good results. Moreover, it is presumed as a sturdy package to evaluate the performance of any solar cells and modules in changing metrological conditions. Hence, this will assist “**Make in India**” mission in the sector of PV manufacturing.

## Nomenclature

### Abbreviations

PV system	Photovoltaic system
STC	Standard Test Conditions
SRRA	Solar Radiation Resources Assessment
MNRE	Ministry of New and Renewable Energy
CEA	Central Electricity Authority
RE	Relative Error

## Symblos

q	Charge of an electron = $1.602 \times 10^{-19}$ C
K	Boltzmann's constant = $1.380 \times 10^{-23}$ J/K
E <sub>g</sub>	Forbidden Energy band gap, for silicon = 1.1 eV
A	Ideality factor of the diode
I <sub>d</sub>	Diode current [A]
N <sub>s</sub>	Number of cells connected in series
N <sub>p</sub>	Number of cells connected in parallel
Trtc	Real-time temperature [°C]
Trc	Reference temperature [°C]
T <sub>o</sub>	Real-time temperature [K]
T <sub>r</sub>	Reference temperature [K]
I <sub>ph</sub>	Photocurrent of a solar PV cell generated due to solar irradiation [A]
I <sub>sc</sub>	Short-circuit current at STC [A]
K <sub>i</sub>	Temperature coefficient of I <sub>sc</sub> cell short circuit current [0.005254 A/°C]
G	Solar irradiance [W/m <sup>2</sup> ]
G <sub>ref</sub>	Solar Irradiance at STC [W/m <sup>2</sup> ]
V <sub>oc</sub>	Open circuit voltage [V]
I <sub>rs</sub>	Diode reverse saturation current at Trtc [A]
R <sub>s</sub>	Series resistance of the PV module [Ω]
R <sub>p</sub>	Parallel resistance of the PV module [Ω]
V	Output voltage from the PV panel [V]
I	Output current from the PV panel [A]
V <sub>in</sub>	Ramp voltage [V]
P <sub>m</sub>	Maximum power at STC [W]
V <sub>mp</sub>	Maximum power voltage [V]
I <sub>mp</sub>	Maximum power current [A]
η	Efficiency of PV panel [%]

## References

- AbdelHady, R., 2017. Modeling and simulation of a micro grid-connected solar PV system. *Water Sci.* 31 (1), 1–10. <http://dx.doi.org/10.1016/j.wsj.2017.04.001>.
- Abdulkadir, M., Samosir, A.S., Yatim, A.H.M., 2012. Modeling and simulation based approach of photovoltaic system in simulink model. *J. Eng. Appl. Sci. (ARPN)* 7 (5), 616–623.
- Abdullahi, N., Saha, C., Jinks, R., 2017. Modeling and performance analysis of a silicon PV module. *J. Renew. Sustain. Energy* 9 (3), 1–11. <http://dx.doi.org/10.1063/1.4982744>.
- Adamo, F., Attivissimo, F., Di Nisio, A., Spadavecchia, M., 2011. Characterization and testing of a tool for photovoltaic panel modeling. *IEEE Trans. Instrum. Meas.* 60 (5), 1613–1622. <http://dx.doi.org/10.1109/TIM.2011.2105051>.
- Altas, I.H., Sharaf, A.M., 2007. A photovoltaic array simulation model for Matlab-Simulink GUI environment. In: *Clean Electrical Power, 2007. ICCEP. IEEE*, pp. 341–345. <http://dx.doi.org/10.1109/ICCEP.2007.384234>.
- Amrani, O., Rekioua, D., 2006. Etude et identification des différents modèles Electriques photovoltaïques. In: *International Conference ICEA, Vol. 6*.
- Amrouche, S.O., Rekioua, D., Rekioua, T., Bacha, S., 2016. Overview of energy storage in renewable energy systems. *Int. J. Hydrogen Energy* 41 (45), 20914–20927. <http://dx.doi.org/10.1016/j.ijhydene.2016.06.243>.
- Aneke, M., Wang, M., 2016. Energy storage technologies and real-life applications—A state of the art review. *Appl. Energy* 179, 350–377. <http://dx.doi.org/10.1016/j.apenergy.2016.06.097>.
- Aoun, N., Chenni, R., Nahman, B., Bouchouicha, K., 2014. Evaluation and validation of equivalent five-parameter model performance for photovoltaic panels using only reference data. *Energy Power Eng.* 6 (09), 235. <http://dx.doi.org/10.4236/epe.2014.69021>.
- Banu, I.V., Istrate, M., 2012. Modeling and simulation of photovoltaic arrays. *Bul. AGIR* 3, 161–166. <http://www.buletinulagir.agir.ro/articol.php?id=1378>.
- Bellini, A., Bifaretti, S., Iacovone, V., Cornaro, C., 2009. Simplified model of a photovoltaic module. In: *Applied Electronics. IEEE*, pp. 47–51.
- Central Electricity Authority, 2017a. Growth of electricity sector in India from 1947–2017, pp. 1–83. [http://www.cea.nic.in/reports/others/planning/pdm/growth\\_2017.pdf](http://www.cea.nic.in/reports/others/planning/pdm/growth_2017.pdf).
- Central Electricity Authority, 2017b. All India installed capacity of power stations, pp. 1–7. [www.cea.nic.in/reports/monthly/installedcapacity/2017/installed\\_capacity-10.pdf](http://www.cea.nic.in/reports/monthly/installedcapacity/2017/installed_capacity-10.pdf).
- Dewangan, P.K., Goswami, A., Dewangan, S.K., 2015. Mathematical Model of 72W Cosmic Module with Matlab/Simulink. *SSRG Int. J. Electr. Electron. Eng. (SSRG-IJEEE)* 2 (5), 15–21.
- Fara, L., Craciunescu, D., 2017. Output analysis of stand-alone PV systems: modeling, simulation and control. *Energy Procedia* 112, 595–605. <http://dx.doi.org/10.1016/j.egypro.2017.03.1125>.
- Geonka, D., Guttikunda, S., 2012. Coal Kills: An Assessment of Death and Disease Caused by India's Dirtiest Energy Source. Urban Emissions in partnership with the Conservation Action Trust and Greenpeace India. [http://www.greenpeace.org/india/Global/india/report/Coal\\_Kills.pdf](http://www.greenpeace.org/india/Global/india/report/Coal_Kills.pdf).
- Gould, T., 2015. World energy outlook special report 2015. Paris. In: *OECD/International Energy Agency. International Energy Agency, Paris*, pp. 1–19. [https://www.iea.org/publications/freepublications/publication/IndiaEnergyOutlook\\_WEO2015.pdf](https://www.iea.org/publications/freepublications/publication/IndiaEnergyOutlook_WEO2015.pdf).
- Hamdi, R.T.A., 2017. Solar cell system simulation using Matlab-Simulink. *Kurdistan J. Appl. Res.* 2 (1), 45–51. <http://dx.doi.org/10.24017/science.2017.1.4>.
- Hashim, E.T., Khazaa, S.Q., 2017. Modelling and output power evaluation of series-parallel photovoltaic modules. *Int. J. Comput. Appl.* 158 (8), 35–46. <http://dx.doi.org/10.5120/ijca2017912846>.
- Hemmati, R., 2018. Optimal design and operation of energy storage systems and generators in the network installed with wind turbines considering practical characteristics of storage units as design variable. *J. Cleaner Prod.* 185, 680–693. <http://dx.doi.org/10.1016/j.jclepro.2018.03.062>.
- Hemmati, R., Saboori, H., 2016. Emergence of hybrid energy storage systems in renewable energy and transport applications—A review. *Renew. Sustain. Energy Rev.* 65, 11–23. <http://dx.doi.org/10.1016/j.rser.2016.06.029>.
- Kanchan, S., Kumarankandath, A., 2015. The Indian power sector: Need of sustainable energy access, IPPAI knowledge report, 126–140. [http://cdn.cseindia.org/attachments/061046700\\_1505884602\\_The-Indian-Power-Sector.pdf](http://cdn.cseindia.org/attachments/061046700_1505884602_The-Indian-Power-Sector.pdf).
- Kharb, R.K., Shimi, S.L., Chatterji, S., 2013. Improved maximum power point tracking for solar PV module using ANFIS. *Int. J. Curr. Eng. Technol.* 3 (5), 1878–1885.
- Kim, H., Jung, T.Y., 2018. Independent solar photovoltaic with Energy Storage Systems (ESS) for rural electrification in Myanmar. *Renew. Sustain. Energy Rev.* 82, 1187–1194. <http://dx.doi.org/10.1016/j.rser.2017.09.037>.
- Kirmani, S., Jamil, M., Rizwan, M., 2015. Empirical correlation of estimating global solar radiation using meteorological parameters. *Int. J. Sustain. Energy* 34 (5), 327–339. <http://dx.doi.org/10.1080/14786451.2013.826222>.
- Krisnadinata, Rahim, N.A., Ping, H.W., Selvaraj, J., 2013. Photovoltaic module modeling using Simulink/Matlab. *Procedia Environ. Sci.* 17, 537–546. <http://dx.doi.org/10.1016/j.proenv.2013.02.069>.
- Lyden, S., Haque, M.E., Gargoom, A., Negnevitsky, M., Muoka, P.I., 2012. Modeling and parameter estimation of photovoltaic cell. In: *Power Engineering Conference, AUPEC. IEEE*, pp. 1–6.
- Meflah, A., Rahmoun, K., Mahrane, A., Chikh, M., 2017. Outdoor performance modeling of three different silicon photovoltaic module technologies. *Int. J. Energy Environ. Eng.* 8 (2), 143–152. <http://dx.doi.org/10.1007/s40095-017-0228-6>.
- Mendalek, N., Al-Haddad, K., 2017. Photovoltaic system modeling and simulation. In: *Industrial Technology, ICIT. IEEE*, pp. 1522–1527. <http://dx.doi.org/10.1109/ICIT.2017.791592>.
- Ministry of New and Renewable Energy (MNRE), 2017. Annual Report-MNRE 2016–2017, 1–224. <http://mnre.gov.in/file-manager/annual-report/2016-2017/EN/index.html>.
- Mohammedi, A., Rekioua, D., Mezzai, N., 2013. Regular paper experimental study of a PV water pumping system. *J. Electr. Syst.* 9 (2), 212–222.
- Nathan, H.S.K., 2014. Solar energy for rural electricity in India: A misplaced emphasis. *Econ. Polit. Wkly* 49 (50), 60–67. <http://eprints.nias.res.in/921/1/2015-Kristle%20Nathan-EPW.pdf>.
- Pandiarajan, N., Muthu, R., 2011. Mathematical modeling of photovoltaic module with Simulink. In: *Electrical Energy Systems, ICEES. IEEE*, pp. 258–263. <http://dx.doi.org/10.1109/ICEES.2011.5725339>.
- Patel, J., Sharma, G., 2013. Modeling and simulation of solar photovoltaic module using Matlab/Simulink. *Int. J. Res. Eng. Technol.* 2 (3), 225–228.
- Pendem, S.R., Mikkili, S., 2018. Modeling, simulation and performance analysis of solar PV array configurations (Series, Series-Parallel and Honey-Comb) to extract maximum power under Partial Shading Conditions. *Energy Rep.* 4, 274–287. <http://dx.doi.org/10.1016/j.egy.2018.03.003>.
- Qi, C., Ming, Z., 2012. Photovoltaic module Simulink model for a stand-alone PV system. *Phys. Procedia* 24, 94–100.
- Rahman, S.A., Varma, R.K., Vanderheide, T., 2014. Generalised model of a photovoltaic panel. *IET Renew. Power Gener.* 8 (3), 217–229. <http://dx.doi.org/10.1049/iet-rpg.2013.0094>.
- Rekioua, D., Matagne, E., 2012. Optimization of Photovoltaic Power Systems: Modeling, Simulation and Control. Springer Science & Business Media, <http://dx.doi.org/10.1007/978-1-4471-2403-0>.
- Saboori, H., Hemmati, R., Ghiasi, S.M.S., Dehghan, S., 2017. Energy storage planning in electric power distribution networks—A state-of-the-art review. *Renew. Sustain. Energy Rev.* 79, 1108–1121. <http://dx.doi.org/10.1016/j.rser.2017.05.171>.
- Salem, F.A., 2014. Modeling and simulation issues on photovoltaic systems, for mechatronics design of solar electric applications. *IPASJ Int. J. Mech. Eng. IJME* 2 (8), 24–47.
- Sera, D., Teodorescu, R., Rodriguez, P., 2007. PV panel model based on datasheet values. In: *Industrial Electronics. IEEE*, pp. 2392–2396. <http://dx.doi.org/10.1109/ISIE.2007.4374981>.

- Shahzad Baig, K., Yousaf, M., 2017. Coal-fired power plants: Emission problems and controlling techniques. *J. Earth Sci. Clim. Change* 8 (404), 1–9. <http://dx.doi.org/10.4172/2157-7617.1000404>.
- Sharma, D.K., Verma, V., Singh, A.P., 2014. Review and analysis of solar photovoltaic software. *Int. J. Curr. Eng. Technol.* 4 (2), 725–731.
- Sindhu, S., Nehra, V., Luthra, S., 2016. Identification and analysis of barriers in implementation of solar energy in Indian rural sector using integrated ISM and fuzzy MICMAC approach. *Renew. Sustain. Energy Rev.* 62, 70–88. <http://dx.doi.org/10.1016/j.rser.2016.04.033>.
- Villalva, M.G., Gazoli, J.R., Ruppert Filho, E., 2009. Comprehensive approach to modeling and simulation of photovoltaic arrays. *IEEE Trans. Power Electron.* 24 (5), 1198–1208. <http://dx.doi.org/10.1109/TPEL.2009.2013862>.
- Yatimi, H., Aroudam, E.H., 2015. A Detailed Study and Modeling of Photovoltaic Module under Real Climatic Conditions. <http://dx.doi.org/10.12720/ijeee.3.3.171-176>.
- Yildiran, N., Tacer, E., 2016. Identification of photovoltaic cell single diode discrete model parameters based on datasheet values. *Sol. Energy* 127, 175–183. <http://dx.doi.org/10.1016/j.solener.2016.01.024>.