Contents list available at IJRED website
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***Research Article***

# Mathematical Modelling of Solar Photovoltaic Cell/Panel/Array Based on the Physical Parameters from the Manufacturer's Datasheet

Manoharan Premkumar[a*], Chandrasekaran Kumar[b], Ravichandran Sowmya[c]

[a]*Department of EEE, GMR Institute of Technology, Rajam, Andhra Pradesh, India*

[b]*Department of EEE, Bannari Amman Institute of Technology, Sathyamangalam, Tamil Nadu, India*

[c]*Department of EEE, National Institute of Technology, Tiruchirapalli, Tamil Nadu, India*

**ABSTRACT**. This paper discusses a modified V-I relationship for the solar photovoltaic (PV) single diode based equivalent model. The model is derived from an equivalent circuit of the PV cell. A PV cell is used to convert the solar incident light to electrical energy. The PV module is derived from the group of series connected PV cells and PV array, or PV string is formed by connecting the group of series and parallel connected PV panels. The model proposed in this paper is applicable for both series and parallel connected PV string/array systems. Initially, the V-I characteristics are derived for a single PV cell, and finally, it is extended to the PV panel and, to string/array. The solar PV cell model is derived based on five parameters model which requires the data's from the manufacturer's data sheet. The derived PV model is precisely forecasting the P-V characteristics, V-I characteristics, open circuit voltage, short circuit current and maximum power point (MPP) for the various temperature and solar irradiation conditions. The model in this paper forecasts the required data for both polycrystalline silicon and monocrystalline silicon panels. This PV model is suitable for the PV system of any capacity. The proposed model is simulated using Matlab/Simulink for various PV array configurations, and finally, the derived model is examined in partial shading condition under the various environmental conditions to find the optimal configuration. The PV model proposed in this paper can achieve 99.5% accuracy in producing maximum output power as similar to manufacturers datasheet. 

***Keywords:*** Forecasting, I-V characteristics, MPP, Partial shading, P-V characteristics, PV cell

**Article History**: Received: Oct 24, 2019; Revised: January 27, 2020; Accepted: February 04, 2020; Available online: February 15, 2020
**How to Cite This Article**: Premkumar, M., Kumar, C., and Sowmya, R. (2020) Mathematical Modelling of Solar Photovoltaic Cell/Panel/Array based on the Physical Parameters from the Manufacturer's Datasheet. Int. Journal of Renewable Energy Development, 9(1), 7-22
https://doi.org/10.14710/ijred.9.1.7-22

## 1. Introduction

Due to the rapid growth in renewable energy sources, the PV power market is rapidly expanded, especially in distributed generation field. So, the PV designers are in need of a reliable and flexible tool to predict the power generation by the PV systems of various sizes. The solar PV modeling is being updated endlessly to help the researchers for a better understanding of the operation. Depends on the various simulation software's such as Matlab, Simulink, C-program, Sci-lab, LTSpice, etc., the developed PV model differs from each other. However, most of the mathematical models are developed based on the voltage (V) – current (I) relations that result from simplifications to two-diode PV model presented by Chan & Phang 1987. The V-I relations for the one-diode model takes responsibility that one diode is sufficient to define the PV cell characteristics. This V-I relation is the basis for all the PV cell modeling. The simplification to V-I relation is done by considering infinite shunt resistance, and this is the basis for four parameter PV cell model. A simplified explicit model was developed by Chenni *et al.* (2007) by considering the short-circuit current of the cell is equal to the photocurrent. To solve the problem of deriving the maximum power output from the PV cell, Zhou *et al.* (2007) proposed the concept of fill factor.

The researchers such as Walker (2001); Premkumar *et al.* (2019); Ahmadi *et al.* (2018); Premkumar *et al.* (2018a); Longatt (2005); and Nguyen & Nguyen (2015) have developed the PV model using Matlab software to find the output PV current from the voltage, cell temperature, and solar irradiation, and discussed the effect on the PV cell due to the change in operating conditions such as cell temperature, diode quality factor, series resistance, and the solar irradiation. However, the readers require a programming skill to understand the overall concepts. Gow and Manning (1999) have developed a model using Matlab and C-programming and it is much difficult to understand the concepts. Among the various

* Corresponding author: mprem.me@gmail.com

researchers, Salmi et al. (2012); Jiang et al. (2011); Sudeepika & Khan (2014); Nema & Agnihotri (2010) and Hossein et al. (2018) have developed a PV model based on the cell/module/array mathematical equations and constructed with the various Simulink blocks. To overcome the problems such as lack of simulation procedure and difficulty, Pandiarajan & Muthu (2011) and Jena *et al.* (2014) have proposed a step-by-step simulation procedure for the PV panel with user-friendly blocks and dialogs in a similar way as proposed by Salmi *et al.* (2012) and Nema & Agnihotri 2010. However, the researchers failed to consider the effect of partial shading on the solar panel.

Banu & Istrate (2012) used an experimental data and curve fitting tool to construct the I-V and P-V characteristics of the solar PV panel. However, it is challenging and unable to collect the data if there is no investigational system exists. Ibbini *et al.* (2014); Ravinder Kumar *et al.* (2014) and Venkateswarlu & Raju (2013) have used a predefined PV block in Simscape, and the parameters such as open circuit voltage, short circuit current, etc. are taken from the manufacturer's datasheet. However, the few parameters such as temperature, saturation current cannot be investigated. Varshney & Tariq (2014), Dehghani *et al.* (2018) and Mohammad *et al.* (2018) discussed a model with two operating conditions such as cell temperature and solar irradiation without the step-by-step procedure.

The model efficiency is improved by adding two additional points along V-I characteristics with additional parameters provided by the National laboratory was proposed by King *et al.* (2004). In this paper, the modified V-I relations was derived using the five parameter model, and it requires manufacturers data. In this paper, the modified V-I relations for a single PV cell is expanded to a PV panel and PV array. The five parameter model was proposed by Desoto *et al.* (2006), and the model uses the V-I relations for a PV cell and only includes cells or panels connected in series.

This paper proposes a modified model to this method to account for parallel and series connections. The model proposed in this paper can be applied to a PV array of any size, and it is suitable for simulation software such as Matlab/Simulink, PSCAD etc. A series of simulation is performed for different PV configuration to validate the performance of the model. The major contribution of this paper is as follows. (i) current source based PV model for simulation studies; (ii) development of V-I characteristics of the PV panel/array; (iii) enhancement of the PV model using the parameters from manufacturers datasheet; (iv) model demonstration and validation through simulation results. The paper is organized as follows: section 2 explains the development of PV cell/module/array characteristics. Section 3 presents the PV model parameters to develop the PV model. The simulation results under various operating conditions are discussed in section 4. Section 5 concludes the paper.

## 2. Development of the I-V Characteristics

The researchers require a reliable and flexible model to precisely forecasts the power generated by PV cells when connected in parallel/series.

### *2.1 I-V Characteristics for Single PV Cell*

An equivalent model conventionally represents the PV cell, and it consists of a diode in anti-parallel, one current source, a shunt & series resistance (Chan & Phang, 1987; Masters, 2004; Jain & Kapoor, 2004; Desoto et al. 2006; and Premkumar *et al.* 2018b). The modified PV cell model is shown in Figure 1. The conventional equivalent circuit is slightly modified by replacing the diode with external current source controlled by diode current and the photocurrent.

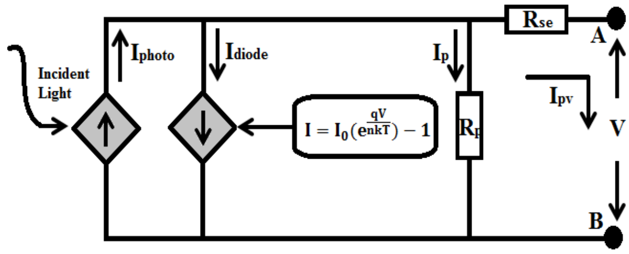


**Fig. 1** Equivalent PV cell model

Apply Kirchhoff's current law in the model shown in Figure 1. The total PV current is presented in Equation 1.

$$I_{pv} = I_{photo} - I_{diode} - I_p \tag{1}$$

Where $I_{photo}$ is an irradiance current or the photocurrent when the PV cell is visible to incident sunlight. The photocurrent is linearly varying concerning solar irradiance at a certain temperature. $I_{diode}$ is an anti-parallel diode current, and it produces the non-linear response on the PV cell. The current flow through the shunt resistor is represented by $I_p$. Substitute the expression for $I_p$ and $I_{diode}$ in Equation 1, and the PV current is derived in Equation 2.

$$I_{pv} = I_{photo} - I_0(e^{\frac{q(V+I_{pv}R_{se})}{nkT}} - 1) - (\frac{V+I_{pv}R_{se}}{R_p}) \tag{2}$$

Where q = 1.602×$10^{-19}$ C, the diode ideality factor is represented by n, Boltzmann constant represented as k = 1.3806503×$10^{-23}$ J/K, Io is the saturation current of the diode, the temperature of the PV cell is represented by T, $R_p$ & $R_{se}$ represents the shunt and series resistance, respectively.

### *2.2 I-V Characteristics of the PV Module*

The PV module/panel comprises a number of series connected PV cells, and Ns represents a series-connected PV cell. For example, BP Solar BP170B panel consists of $N_s$=72, and SunPower SPR-76R-BLK-U panel consists of $N_s$=24. The output current ($I_{pv,P}$) in terms of the output voltage ($V_P$) of the PV module when $N_s$ cells are connected in series is represented in Equation 3.

$$I_{pv,P} = I_{photo} - I_0(e^{\frac{q(V_P+I_{pv,P}R_{se})}{N_s nkT}} - 1) - (\frac{V_P+I_{pv,P}R_{se}N_s}{N_s R_p}) \tag{3}$$

Equation 3 is extended to any value of Ns, and it is applicable to any PV module. $N_{ps}$ represent the number of panels connected in series, and $N_{pvs}$ represent the number of series connected PV cells in each panel, and now, $N_s$ is rewritten as per Equation 4.

$$N_s = N_{ps} * N_{pvs} \quad (4)$$

*2.3 I-V Characteristics of the PV String*

In the PV array, the PV modules are connected in series and parallel combinations. To start with the I-V characteristics for a single PV cell; the number of PV cells connected in series to derive a PV string and I-V characteristics is developed for a number of strings connected in parallel to derive an array. The configuration of the PV array is shown in Figure 2. The series connected cells are represented by $N_s$ and the parallel connected PV strings are represented by $N_p$. The PV array's output voltage ($V_{ar}$) and the output current ($I_{ar}$) is presented in Equation 5.

$$I_{ar} = N_p I_{photo} - N_p I_0 (e^{\frac{q\left(V_{ar}+I_{ar}\frac{N_s}{N_p}R_{se}\right)}{N_s n k T}} - 1) - \left(\frac{V_{ar}+I_{ar}R_{se}\frac{N_s}{N_p}}{\frac{N_s}{N_p}R_p}\right) \quad (5)$$

The mathematical modeling of the PV array system in Matlab/Simulink software is done by using Equation 5. With the help of following assumptions such as $N_p I_{photo} = I'_{photo}$, $N_p I_o = I'_o$, $\frac{N_s}{N_p} R_{se} = R'_{se}$, and $\frac{N_s}{N_p} R_p = R'_p$, Equation 5 is modified as Equation 6.

$$I_{ar} = I'_{photo} - I'_o (e^{\frac{q(V_{ar}+I_{ar}R'_{se})}{N_s n k T}} - 1) - (\frac{V_{ar}+I_{ar}R'_{se}}{R'_p}) \quad (6)$$

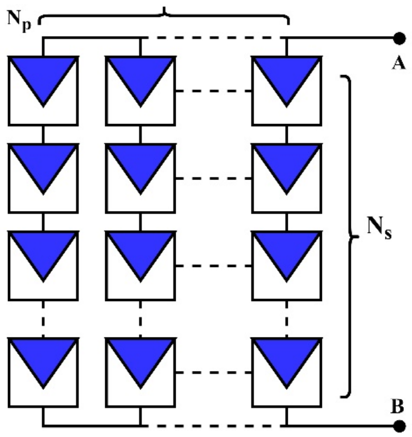

**Fig. 2.** Configuration of the PV Array

With the same assumptions, Equation 6 is similar to the I-V relation for a single PV cell and, it is proved that the PV array equivalent circuit is similar to the PV cell equivalent circuit. However, the variables in Figure 1 and the variables in Equation 6 have different meaning based on the above assumptions, and the additional controlled current source has different control.

## 3. Important Parameters of the PV Model

Before mathematical modeling of the PV cell, it is essential to study the significance of the PV model parameters and its behavior under a change in environmental conditions (Kim et al. 2009 and King et al. 2004).

*3.1 Ideality Factor (n or η)*

The diode ideality factor is depending on the moving carriers across the junction. If the process is pure diffusion, the value of n is 1, whereas, for recombination in the depletion region, the value of n is 2. Rajapakse & Muthumuni (2009) suggested the value of n is 1.3 for Si material. In this paper, n is one of the unknown parameters, and the value of n is assumed to be related to the solar cell material and it is independent of the cell temperature and solar irradiation. The value of n can be found by using the known data such as $I_{photo}$, $I_o$, $R_S$, $R_P$ and the manufacturer data such as $V_{oc}$, $I_{sc}$, $V_{mpp}$, $I_{mpp}$, αT, and βT. This value can also be found using Lambert W-Functions (Jain & Kapoor, 2005; Bashahu & Nkundabakura, 2007). The parameter n is a unitless parameter, and it means that the PV cell act as an ideal diode. The operating condition of the cell will not change the value of n. The reference value of n, i.e. $n_{ref}$ is compared with n, and it is presented in Equation 7.

$$n = n_{ref} \text{ at SRC} \quad (7)$$

Where SRC is Standard Reference Condition. The PV cell temperature is represented as $T_{ref}$ = 298 K or 25°C and the solar irradiation is represented as $G_{ref}$ = 1000 W/m$^2$ at SRC.

*3.2 Photocurrent ($I_{photo}$)*

The photocurrent of the PV is depending on the irradiation and the cell temperature. The expression for the photocurrent is given in Equation 8.

$$I_{photo} = I_{photo,ref}\left(\frac{G}{G_{ref}}\right)[1 + \alpha'_T(T - T_{ref})] \quad (8)$$

At SRC, the reference photocurrent is represented by $I_{photo,ref}$ and it is an unknown parameter for the PV model. $\alpha'_T$ is relative temperature coefficient of the short-circuit current (SCC) and it represents the rate of change of the SCC with respect to temperature. Sometimes, the manufacturers of the panel provide the detail on the absolute temperature coefficient of the SCC ($\alpha_T$) and the relation between $\alpha_T$ and $\alpha'_T$ is presented in Equation 9.

$$\alpha_T = \alpha'_T * I_{photo,ref} \quad (9)$$

*3.3 Diode Saturation Current ($I_0$)*

The saturation current of the diode ($I_o$) is presented in Equation 10, and it is depending on the PV cell temperature.

$$I_o = I_{o,ref}\left[{}^{T}/_{T_{ref}}\right]^3 e^{\left[\frac{E_{g,ref}}{kT_{ref}} - \frac{E_g}{kT}\right]} \quad (10)$$

Where $I_{o,ref}$ is diode saturation current at SRC and this parameter also an unknown parameter of the PV model. The band gap energy is represented by $E_g$ (Kim et al. 2009) and the expression for $E_g$ is presented in Equation 11. The relationship between the temperature and bandgap energy for the different material is shown in Figure 3.

$$E_g = 1.16 - 7.02 * 10^{-4}\left[\frac{T^2}{T-1108}\right] \tag{11}$$

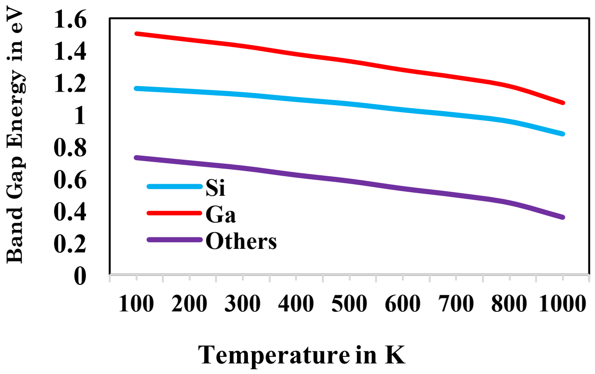


**Fig. 3** Temperature vs Bandgap Energy

### *3.4 PV Cell Temperature (T)*

The PV cell temperature varies when the solar insolation and the environment temperature changes. The expression for the cell temperature is presented in Equation 12.

$$T = T_{amb} + \left[\frac{NOCT - 20^oC}{0.8}\right] G \tag{12}$$

The ambient temperature is represented as $T_{amb}$ and the nominal operating cell temperature (NOCT) is issued by the manufacturers. The solar irradiation at ambient temperature is represented by $G_{amb}$ (Duffie & Beckman 2006). The cell temperature is also expressed by including heat loss coefficients, and the expression is presented in Equation 13.

$$\frac{T - T_{amb}}{T_{NOCT} - T_{amb,NOCT}} = \frac{G_{amb}}{G_{NOCT}}\frac{U_{L,NOCT}}{U_L}\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{13}$$

Where $T_{NOCT}$ is the cell temperature at the normal operating condition, $T_{amb,NOCT}$ is 20ºC, the solar irradiation at ambient temperature is $G_{amb}$, $G_{NOCT}$ is equal to 800 W/m², $U_L$ and $U_{L,NOCT}$ is heat loss coefficient at the actual operating condition and NOCT condition. The cell efficiency at T is represented by $\eta_c$, $\tau\alpha$ is the emittance and absorptance product. Further, the expression for T is modified and presented in Equation 14.

$$T = \frac{G_{amb}}{G_{NOCT}}\left(NOCT - T_{amb,NOCT}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) + T_{amb} \tag{14}$$

The Equations (12-14) will give the same results at the foreseen cell temperature. To find the value of T, Equations (13-14) will be problematic because of the new unknown parameters involved in the calculation. The cell temperature is calculated as per Equation 12 in this paper.

### *3.5 Series Resistance ($R_{se}$) and Parallel Resistance ($R_p$)*

To derive the PV model, the values of $R_p$ and $R_{se}$ are required. First, $R_p$ is derived by approximation, and it presented in Equation 15.

$$R_p > \frac{10 * V_{oc}}{I_{sc}} \tag{15}$$

Where $I_{sc}$ is short-circuit current and $V_{oc}$ is the open circuit voltage. The relation between the parallel resistance, the solar irradiation at the SRC and the actual operating condition is given in Equation 16.

$$\frac{R_p}{R_{p,ref}} = \frac{G}{G_{ref}} \tag{16}$$

The assumption calculates the value of series resistance, and it is given in Equation 17.

$$R_{se} < \frac{0.1 * V_{oc}}{I_{sc}} \tag{17}$$

The assumption for the series resistance is that it does not depend on the solar irradiation and temperature at SRC and actual operating condition. Again, the series resistance is presented in Equation 18.

$$R_{se} = R_{se,ref} \tag{18}$$

### *3.6 Determination of PV Model Parameters Based on the Manufacturers Datasheet*

From Equation 5, the unknown parameters such as $I_{photo,ref}$, $I_{o,ref}$, $n_{ref}$, $R_{se,ref}$ and $R_{p,ref}$ are solved by using the I-V relationship of the mathematical PV model. The PV model utilizes the manufacturer's data to get accurate results (Desoto *et al.* 2006). Except for the variable under NOCT, the data under SRC is provided such as the solar irradiation 800 W/m² and air mass modifier (AM) is 1.5 at the nominal operating condition. Few manufacturers provide the nominal operating condition parameters for the PV panel. The model of the system is derived from the following five equations as discussed in Chenni et al. 2007 and Nguyen et al. 2015. The first unknown equation is derived at SRC from the open circuit, where $I_{ar} = 0$ and $V_{ar} = V_{OC,\,ref}$. Equation 5 is replaced by Equation 19.

$$0 = N_p I_{photo,ref} - N_p I_{0,ref}\left(e^{\frac{q(V_{oc,ref})}{N_s n_{ref} k T_{ref}}} - 1\right) - \left(\frac{V_{oc,ref}}{\frac{N_s}{N_p}R_{p,ref}}\right) \tag{19}$$

The second unknown equation happens at SRC under short circuit, where $I_{ar} = I_{sc,\,ref}$, and $V_{ar} = 0$. Thus, Equation 5 is replaced by Equation 20.

$$I_{sc,ref} = N_p I_{photo,ref} - N_p I_{0,ref}\left(e^{\frac{q(I_{sc,ref} * R_{se,ref})}{N_p n_{ref} k T_{ref}}} - 1\right) - \left[\frac{I_{sc,ref} * R_{se,ref} * \frac{N_s}{N_p}}{\frac{N_s}{N_p}R_{p,ref}}\right] \tag{20}$$

The maximum current and maximum voltage at MPP under SRC is taken from the datasheet and substituted in Equation 5 to derive the third unknown equation by assuming $I_{ar}=I_{mpp,\,ref}$ and $V_{ar}=V_{mpp,\,ref}$. Thus, Equation 5 is replaced by Equation 21.

$$I_{mpp,ref} = N_p I_{photo,ref} - N_p I_{0,ref}\left(e^{\frac{q\left(V_{mpp,ref}+I_{mpp,ref}*R_{se,ref}*\frac{N_s}{N_p}\right)}{N_p n_{ref} k T_{ref}}} - 1\right) - \left[\frac{V_{mpp,ref}+I_{mpp,ref}*R_{se,ref}*\frac{N_s}{N_p}}{\frac{N_s}{N_p}R_{p,ref}}\right] \quad (21)$$

At MPP, the power derivative concerning the maximum voltage is equal to zero. At SRC, $\frac{\partial P}{\partial V}|_{P=P_{max}} = 0$. Where P is equal to the multiplication of $V_{ar}$ and $I_{ar}$. The fourth unknown equation is presented in Equation 22.

$$\frac{I_{mpp,ref}}{V_{mpp,ref}} = \frac{\frac{q(N_p I_{o,ref})}{N_s n_{ref} k T_{ref}} e^{\frac{q\left(V_{mpp,ref}+I_{mpp,ref}*R_{se,ref}*\frac{N_s}{N_p}\right)}{N_p n_{ref} k T_{ref}}} + \frac{1}{\frac{N_s}{N_p}R_{p,ref}}}{1+\frac{q(N_p I_{o,ref})}{N_s n_{ref} k T_{ref}} e^{\frac{q\left(V_{mpp,ref}+I_{mpp,ref}*R_{se,ref}*\frac{N_s}{N_p}\right)}{N_s n_{ref} k T_{ref}}} + \frac{R_{se,ref}}{R_{p,ref}}} \quad (22)$$

The final unknown equation confirms the open circuit temperature coefficient ($\beta_T$), and the PV model is forecasting the data appropriately.

$$\text{Temperature coefficient}, \beta_T = \frac{\partial V_{oc}}{\partial T} = \frac{V_{oc}-V_{oc,ref}}{T-T_{ref}} \quad (23)$$

$$V_{oc} = V_{oc,ref} + \beta_T (T - T_{ref}) \quad (24)$$

Very few manufacturers provide the data for relative temperature coefficient ($\beta'_T$) and the relation between $\beta'_T$ and $\beta_T$ are given in Equation 25.

$$\beta_T = \beta'_T V_{oc,ref} \quad (25)$$

$V_{oc}$ from Equation 24 at cell temperature, $T = T_{ref} \pm 10K$ is the open circuit voltage condition. The 10K temperature is an assumption but $T_{ref}$ will give the same answer. An extra temperature can be varied from 1K to 10K. Similar to Equation 19, $V_{oc}$ is obtained from Equation 5 to derive Equation 26.

$$0 = N_p I_{photo} - N_p I_0 (e^{\frac{q(V_{oc}*T)}{N_s n k T}} - 1) - \left[\frac{V_{oc}*T}{\frac{N_s}{N_p}R_p}\right] \quad (26)$$

The reference solar irradiation is assumed as $G=G_{ref}$ to find the parameters such as $n_{ref}$, $I_{o,\,ref}$, $I_{photo,\,ref}$, $R_{se,\,ref}$ and $R_{P,\,ref}$. The Equations (7-8), (10-11), 16, 24 are substituted in Equation 26 to find the fifth unknown Equation to derive the PV model regarding parameter reference. All the equations are solved by using the Matlab/Simulink non-linear equation solver ($f_{solve}$). The first step is to find all the reference parameters then the PV model can prove the effectiveness of the PV array of any capacity at any operating situation. It is necessary to determine the SCC, $V_{mpp}$, and $I_{mpp}$ under the solar irradiation and temperature and the values slightly differ from the reference conditions. The SCC under any operating conditions is presented in Equation 27.

$$I_{sc} = N_p I_{photo} - N_p I_0 (e^{\frac{q(I_{sc}*R_{se})}{N_p n k T}} - 1) - \left[\frac{I_{sc}*R_{se}}{R_p}\right] \quad (27)$$

By using the non-linear equation solver in Matlab/Simulink, the MPP voltage and current can be determined by using Equations (28-29).

$$I_{mpp,ref} = N_p I_{photo} - N_p I_0 \left(e^{\frac{q\left(V_{mpp}+I_{mpp}R_{se}\frac{N_s}{N_p}\right)}{N_s n k T}} - 1\right) - \left[\frac{V_{mpp}+I_{mpp}R_{se}\frac{N_s}{N_p}}{\frac{N_s}{N_p}R_p}\right] \quad (28)$$

$$\frac{I_{mpp}}{V_{mpp}} = \frac{\frac{q(N_p I_o)}{N_s n k T} e^{\frac{q\left(V_{mpp}+I_{mpp}R_{se}\frac{N_s}{N_p}\right)}{N_p n_{ref} k T_{ref}}} + \frac{1}{\frac{N_s}{N_p}R_p}}{1+\frac{q(R_{se} I_o)}{n k T} e^{\frac{q\left(V_{mpp}+I_{mpp}R_{se}\frac{N_s}{N_p}\right)}{N_s n k T}} + \frac{R_{se}}{R_p}} \quad (29)$$

## 4. Simulation Results and Discussions

The PV model is developed using Matlab/Simulink with the help of unknown equations derived from Equations (19-29). The PV model is tested for a few PV panels and the result obtained from the model is constant as the data given by the panel manufacturers. The data given by the manufacturers are suitable for different irradiation and temperature conditions. For simplified analysis, the simulation results obtained for three different rating panels are presented in this paper. The selected panel includes BP Solar BP365TS, BP Solar BP3230T, and SunPower SPR-200-WHT-U. The model parameters are calculated as per the equation for BP Solar BP365TS, BP Solar BP3230T, and SunPower SPR-200-WHT-U panel and listed in Table 1.

Since the derived expressions are non-linear, the simulation results are very much sensitive for the values listed in Table 1 at reference conditions. With the help of the data provided by the manufacturer, the PV module is modeled in Matlab/Simulink, and the model is shown in Figure 4.

**Table 1**
Reference parameters of the PV model

| Parameters | BP Solar BP365TS | BP Solar BP3230T | SunPower SPR-200-WHT-U |
|---|---|---|---|
| $I_{photo,ref}$(A) | 8.1225 | 8.4929 | 5.4103 |
| $I_{0,ref}$(A) | $2.1008.10^{-10}$ | $1.4902.10^{-10}$ | $1.2832\ .10^{-11}$ |
| $R_{se,ref}(\Omega)$ | 0.13134 | 0.41305 | 0.4427 |
| $R_{p,ref}(\Omega)$ | 49.95 | 179.89 | 232.82 |
| $n_{ref}$ | 0.9768 | 0.9624 | 0.96675 |

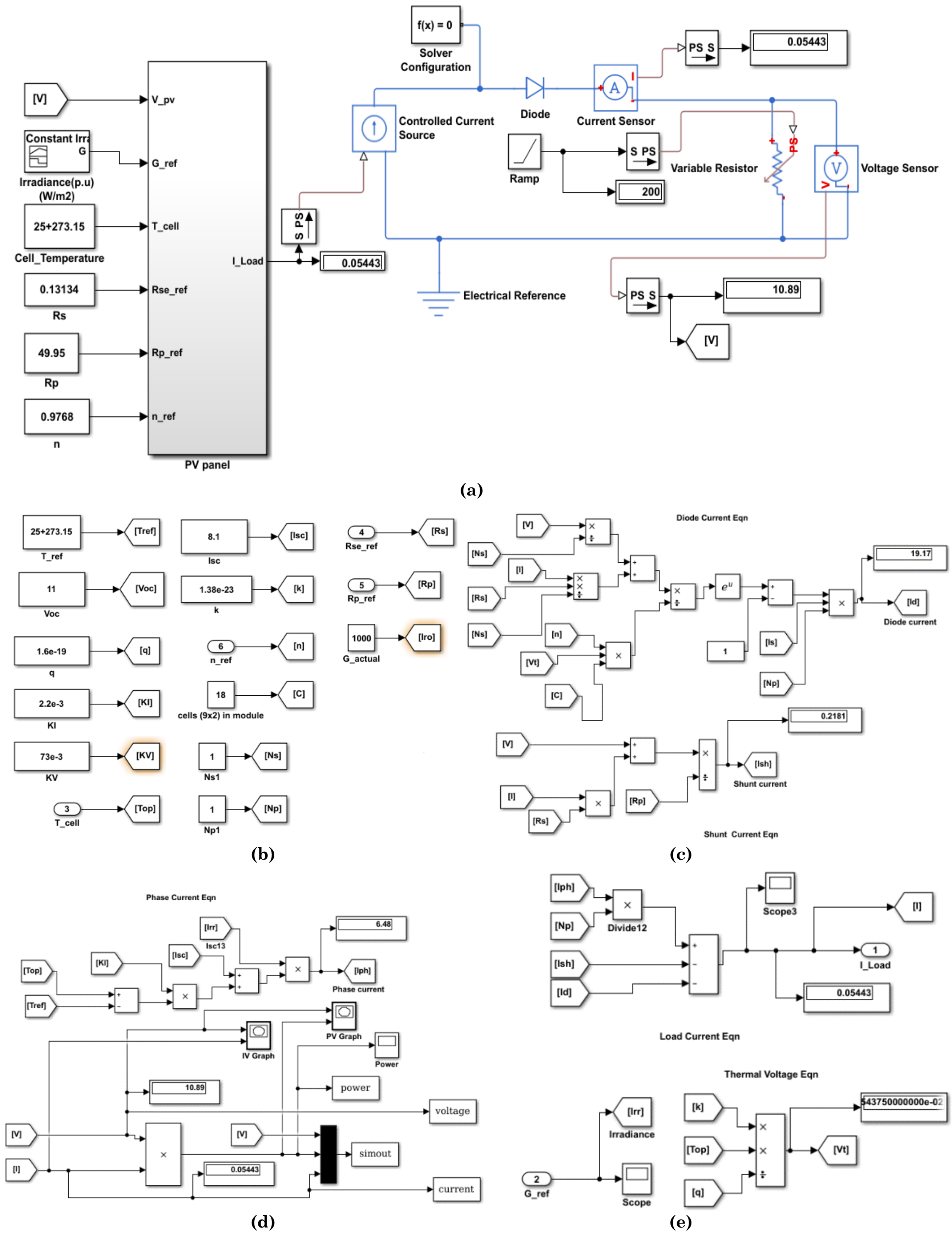


**Fig. 4** Overall PV model; (a) The PV panel model; (b) various parameter initialization, (c) model for shunt current and diode current, (d) model for phase current, (e) model for load current and thermal voltage and various solar irradiation: 1000 W/m²; 750 W/m²; 500 W/m²; 250 W/m²

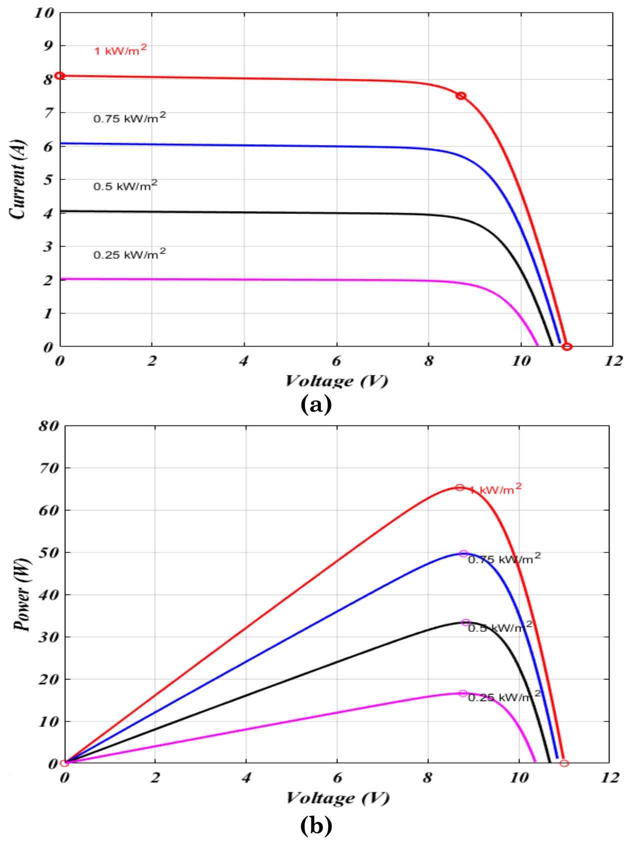


**Fig. 5** I-V and P-V characteristics for BP Solar BP365TS PV panel at 25$^o$C constant temperature

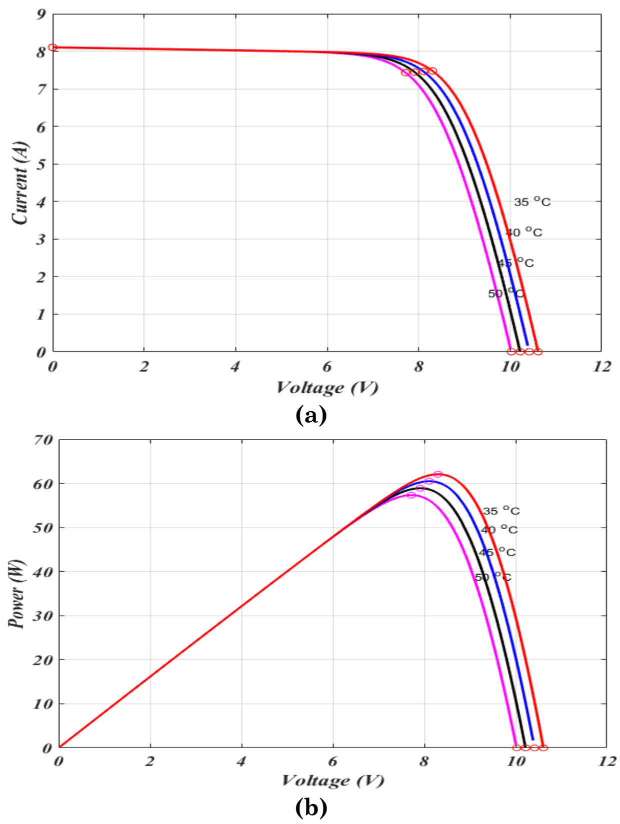


**Fig. 6** I-V and P-V characteristics for BP Solar BP365TS PV panel at the constant irradiation of 1000 W/m$^2$ and various cell temperature: 50$^o$C; 45$^o$C; 40$^o$C; 35$^o$C

To define the I-V and P-V characteristics of the PV panel are depends on the accuracy of the reference parameters for various operating conditions. The parameters listed in Table 1 are the physical parameters and these values are taken from the datasheet of the module. Figure 5 shows the PV model's I-V characteristics for BP Solar BP365TS module at 25$^o$C constant cell temperature and the various solar irradiations: 1000 W/m$^2$; 750 W/m$^2$; 500 W/m$^2$; 250 W/m$^2$. From I-V characteristics, it is observed that $I_{sc}$ and $V_{oc}$ are almost the same as that of the real values.

Figure 6 shows the PV model's I-V characteristics for BP Solar BP365TS module at the constant irradiation of 1000 W/m$^2$ and the change in temperatures: 50$^o$C; 45$^o$C; 40$^o$C; 35$^o$C. From I-V characteristics, it is observed that $I_{sc}$ and $V_{oc}$ are almost the same as that of the real values.

The effectiveness of the PV model is to predict the $V_{oc}$, $I_{sc}$ and the $P_{out}$ accurately for both the NOCT and SRC conditions. The physical parameter such as $V_{oc}$, $I_{sc}$, $V_{mpp}$, $I_{mpp}$, and $P_{max}$ at 25$^o$C constant temperature is compared with the parameters predicted by the PV model, and the comparison is presented in Table 2.

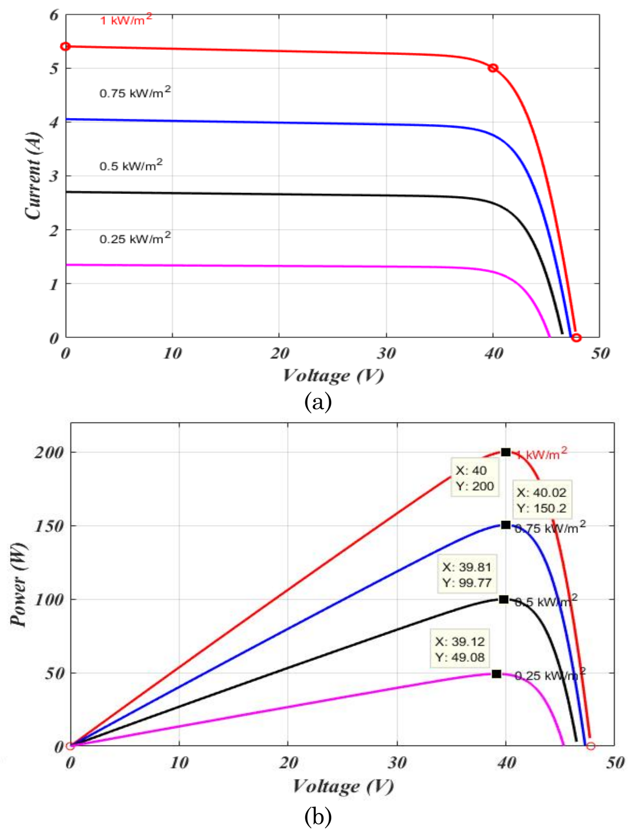


**Fig. 7** I-V and P-V characteristics for Sunpower SPR-200-WHT-U PV panel at the constant temperature of 25$^o$c and various solar irradiation: 1000 W/m$^2$; 750 W/m$^2$; 500 W/m$^2$; 250 W/m$^2$

To check the effectiveness of the PV model, I-V and P-V characteristics of the PV model for SunPower SPR-200-WHT-U panel is also presented in Figure 7 at a 25$^o$C constant temperature under various solar irradiation levels. The MPP for each operating condition is presented in Table 3. The MPP values from the datasheet and the derived PV model are compared in Table 3 and it is observed that the predicted values are accurate. During nominal operating condition, the model shows a very small variation in the prediction, but at the standard operating condition, the predicted values are almost matching the physical values.

**Table 2**
PV model and BP Solar BP365TS parameter comparison

| Operating Conditions | Parameters | BP Solar BP365TS | |
|---|---|---|---|
| | | Model | Datasheet |
| **SRC 1000 W/m²  25°C** | $V_{oc}$ (V) | 11 | 11 |
| | $I_{sc}$ (A) | 8.1 | 8.1 |
| | $V_{mpp}$ (V) | 8.7 | 8.7 |
| | $I_{mpp}$ (A) | 7.5 | 7.5 |
| | $P_{max}$ (W) | 65.25 | 65 |
| **NOCT 800 W/m² 47°C** | $V_{oc}$ (V) | 9.5 | 9.7 |
| | $I_{sc}$ (A) | 7.47 | 7.6 |
| | $V_{mpp}$ (V) | 6.7 | 6.9 |
| | $I_{mpp}$ (A) | 6.95 | 6.7 |
| | $P_{max}$ (W) | 46.7 | 48 |

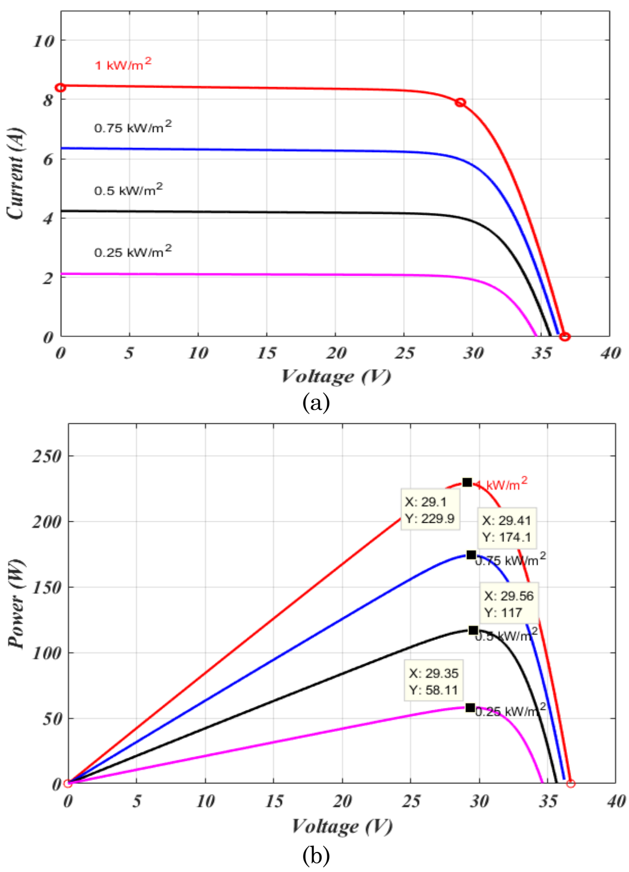


**Fig. 8** I-V and P-V characteristics for BP Solar BP3230T PV panel at the constant temperature of 25°C and various solar irradiation: 1000 W/m²; 750 W/m²; 500 W/m²; 250 W/m²

The I-V and P-V characteristics of the PV model for BP Solar BP3230T panel are shown in Figure 8 at 25°C constant temperature under various solar irradiation levels. The MPP values from the datasheet and the PV model are compared in Table 4 and it is observed that the predicted values are accurate.

**Table 3**
PV model vs SunPower SPR-200-WHT-U parameters

| Operating Conditions | Parameters | SunPower SPR-200-WHT-U | |
|---|---|---|---|
| | | **Model** | **Datasheet** |
| SRC 1000 W/m² 25°C | $V_{oc}$ (V) | 47.8 | 47.8 |
| | $I_{sc}$ (A) | 5.4 | 5.4 |
| | $V_{mpp}$ (V) | 40 | 40 |
| | $I_{mpp}$ (A) | 5 | 5 |
| | $P_{max}$ (W) | 199.75 | 200 |
| NOCT 800 W/m² 47°C | $V_{oc}$ (V) | 43.1 | 44.5 |
| | $I_{sc}$ (A) | 4.24 | 4.38 |
| | $V_{mpp}$ (V) | 37.2 | 36.5 |
| | $I_{mpp}$ (A) | 3.85 | 4.01 |
| | $P_{max}$ (W) | 143.7 | 146 |

During nominal operating condition, the model shows a small variation in prediction, but at the standard operating condition, the predicted values are almost matching the physical values.

**Table 4**
PV Model and BP Solar BP365TS Parameter Comparison

| Operating Conditions | Parameters | BP Solar BP3230T | |
|---|---|---|---|
| | | **Model** | **Datasheet** |
| **SRC 1000 W/m² 25°C** | $V_{oc}$ (V) | 36.7 | 36.7 |
| | $I_{sc}$ (A) | 8.4 | 8.4 |
| | $V_{mpp}$ (V) | 29.1 | 29.1 |
| | $I_{mpp}$ (A) | 7.9 | 7.9 |
| | $P_{max}$ (W) | 229.9 | 230 |
| **NOCT 800 W/m² 47°C** | $V_{oc}$ (V) | 32.7 | 33.4 |
| | $I_{sc}$ (A) | 6 | 6.8 |
| | $V_{mpp}$ (V) | 25.3 | 25.9 |
| | $I_{mpp}$ (A) | 6.41 | 6.32 |
| | $P_{max}$ (W) | 162.4 | 165.6 |

The model developed in this paper helps the researchers to predict the parameters with high accuracy and reliable under various operating conditions. The parameters such as MPP voltage and current, MPP power, open circuit voltage, and SCC are predicted accurately under different operating conditions (various solar irradiations and cell temperatures). The simulation results proved the accuracy of the I-V and P-V relations of the PV model of any ratings. Table 5 presented the physical MPP and predicted MPP for all the three panels at 25°C PV cell temperature and the various levels of solar irradiation: 1000 W/m²; 750 W/m²; 500 W/m²; 250 W/m².

The equivalent circuit and I-V relationship equations are easily modeled and developed by Matlab/Simulink simulation software. The process of deriving the model is straightforward, and it results in accurate predictions. So far, the different types of PV panel under various operating conditions were simulated and discussed. Next sub-chapter explains the effect of shading conditions on the panels.

### *4.1 Effects of Partial Shading on the PV Model*

The derived PV model can also be used to test the partial shading effect on the PV cells in a panel and a PV string and finds better connections based on the bypass diodes. The PV panels are made with the PV cells which are connected in series. The current in all the PV cells is the same. However, the current in the partially shaded cell is more than the SCC, and it happens at a negative voltage region, and it results in negative power. The shaded cell introduces the hotspot because the shaded cells dissipate the heat. In order to overcome this problem, bypass diodes are connected across the panel, and it allows the flow of current around the shaded cell with less voltage loss.

The usage of bypass diodes is explained by considering the SunPower SPR-200-WHT-U panel under the following conditions. Out of 72 cells, 1-18 cells are unshaded; 19-36 cells are completely shaded without bypass diode; 39-54 cells are partially shaded without bypass diodes; 55-72 cells are partially shaded with bypass diodes. The PV model is shown in Figure 9, and the effects of shading on the cells are presented in Figure 10 and Figure 11.

**Table 5**
MPP Power Prediction Comparison under Change in Solar Irradiation

| Solar Irradiation (W/m²) | BP Solar BP365TS | | SunPower SPR-200-WHT-U | | BP Solar BP3230T | |
|---|---|---|---|---|---|---|
| | MPP from Model | MPP from Datasheet | MPP from Model | MPP from Datasheet | MPP from Model | MPP from Datasheet |
| 1000 | 65.25 | 64.94 | 199.75 | 200 | 229.9 | 230 |
| 750 | 50.08 | 51.12 | 150.2 | 152.4 | 174.1 | 175.8 |
| 500 | 34.25 | 33.95 | 99.77 | 102.6 | 117 | 116.5 |
| 250 | 17.5 | 17.95 | 49.08 | 48.2 | 58.1 | 59 |

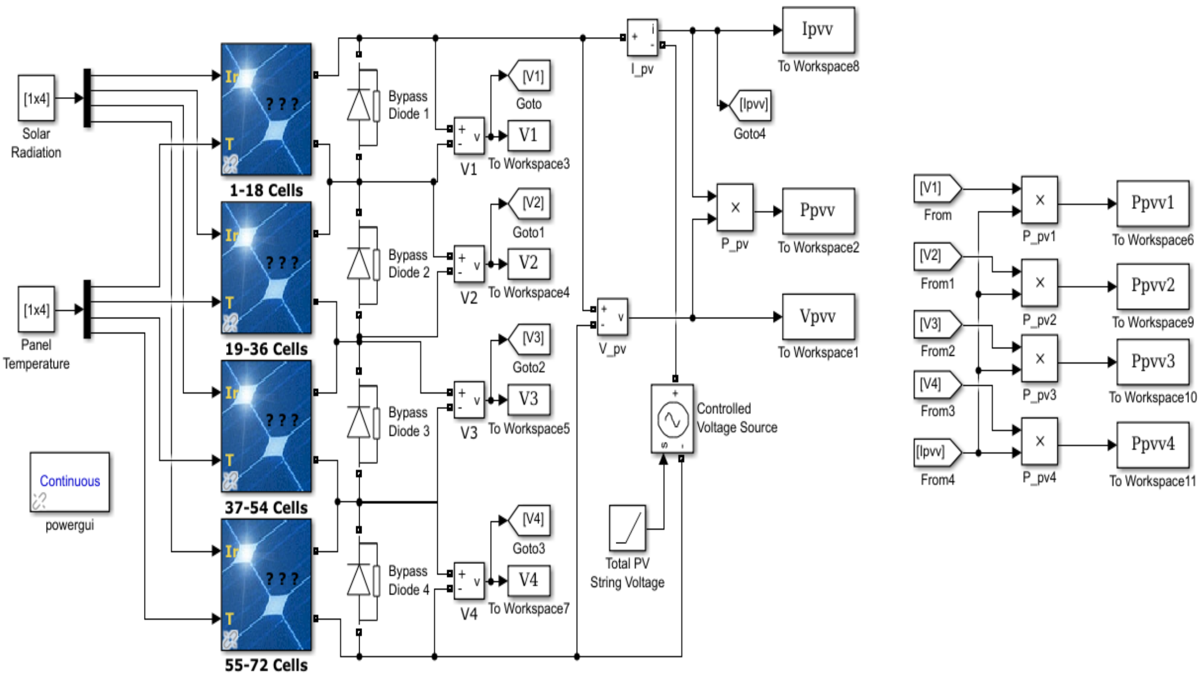


**Fig. 9** Partial shaded SunPower SPR-200-WHT-U panel simulation model

The shading on one set of cell reduces the performance of the PV panel; two sets of cells are shaded causes the reduction in performance further. The I-V characteristics of the shaded panel are shown in Figure 10, and the P-V characteristics of the shaded panel are shown in Figure 11. The unshaded cells from 1-18 are operated at 1000 W/m² solar irradiation; 19-36 cells are operated at 0 W/m² without bypass diode; 39-54 cells are operated at 750 W/m² without bypass diodes; 55-72 cells are operated at 750 W/m² with bypass diodes.

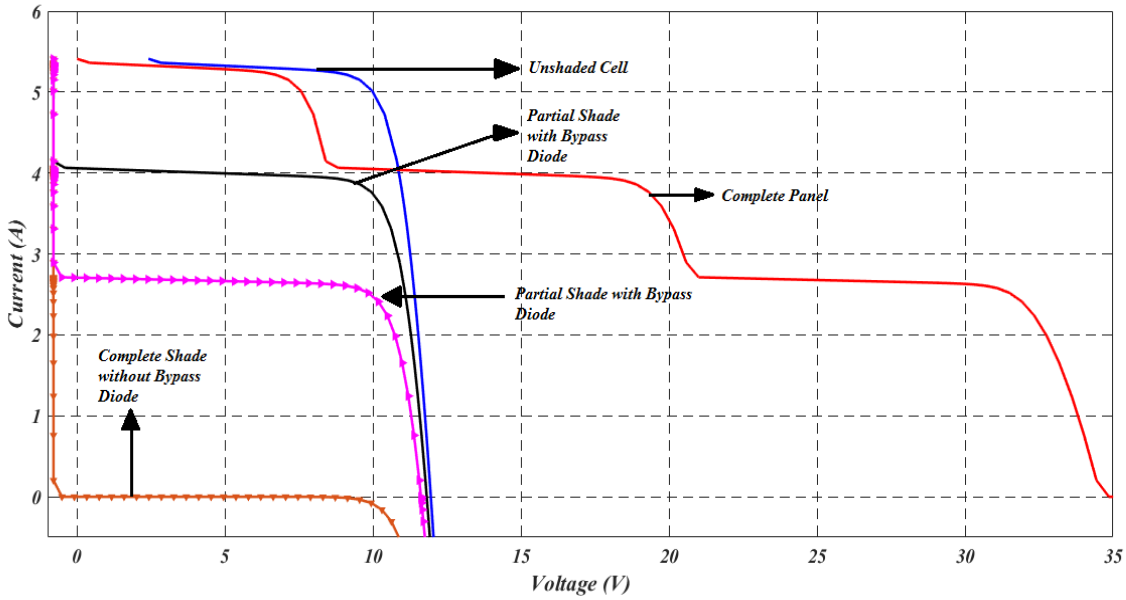


**Fig. 10** I-V Characteristics for the SunPower SPR-200-WHT-U module under unshaded, and partially shaded with/without bypass diode at 25$^0$C cell temperature

In all the shading cases, the I-V and P-V curves of the shaded cells with a bypass diode are similar to the unshaded cell with high power, and it prevents the hotspot issues. The cells from 39-54 and 55-72 are operated at same irradiation level (750 W/m$^2$) without and with bypass diode respectively. The cells from 55-72 exhibit more power than the cells from 39-54 due to the addition of a bypass diode.

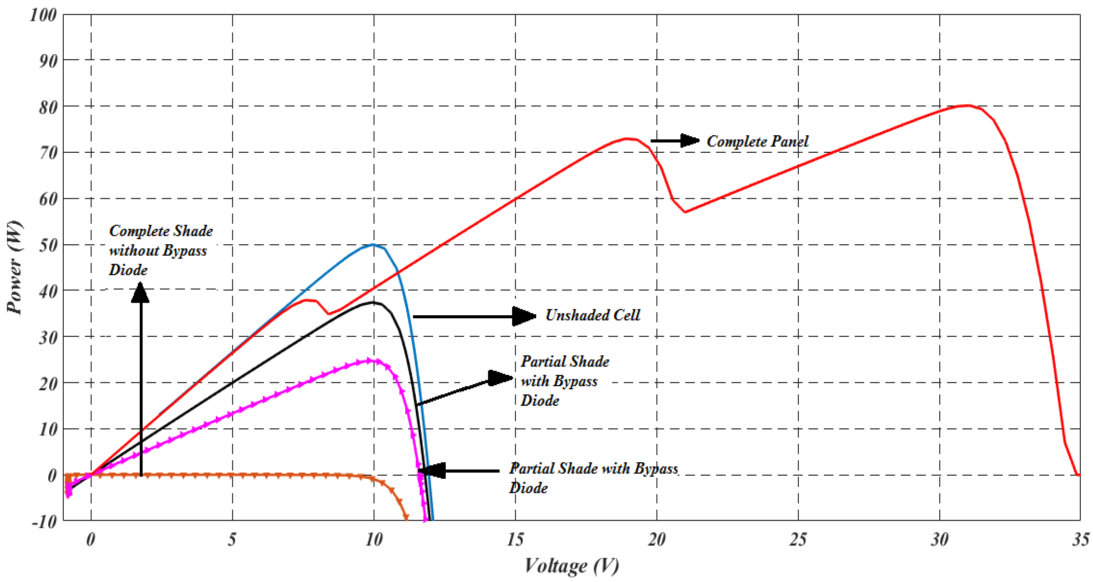


**Fig. 11** P-V characteristics for the SunPower SPR-200-WHT-U module under unshaded, and partially shaded with/without bypass diode at 25$^0$C cell temperature

As per the above discussion, all the PV cells from the panel is provided with bypass diode for the effective tracking of the MPP, but this is not possible in view of designers and manufacturers. Kyocera KC85TS PV module has three bypass diodes. However, most of the manufacturer is providing one bypass diode across the module to protect the panel and to improve the power extraction. In large PV string operations, the PV modules are operated at different operating conditions; few panels may get the solar irradiation, and few panels may get the different cell temperature. The model developed in Matlab/Simulink provides an easy way to test the above effects and helps to find the optimum configuration for the PV array. The PV array is made with four SunPower SPR-200-WHT-U panels. The PV array with three different configurations is shown in Figure 12. The three configurations are tested for the various solar irradiation conditions with constant temperature and the various temperatures with constant solar irradiation.

The configuration-I is made with four panels in series connection. The configuration-II is made with four panels in series and parallel connection with two panels in series each. The configuration-III is made with four panels in parallel connection. The PV model for the configuration-I is shown in Figure 13 for a better understanding of the readers.

The shading effects on the PV array with different cases are investigated for various configurations of the solar PV array at various cell temperature or solar irradiation. All the cases are investigated by considering the bypass diodes as well as the different operating conditions. Three different cases such as constant cell temperature with different solar irradiation, constant irradiation with different cell temperature and different cell temperature and solar irradiation are considered for the simulation study. All the configurations result in different MPP assuming the PV arrays operated at MPP.

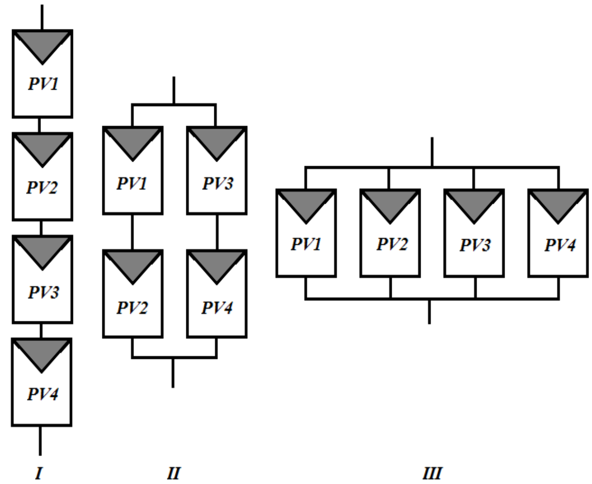


**Fig. 12** Possible solar PV configurations for testing

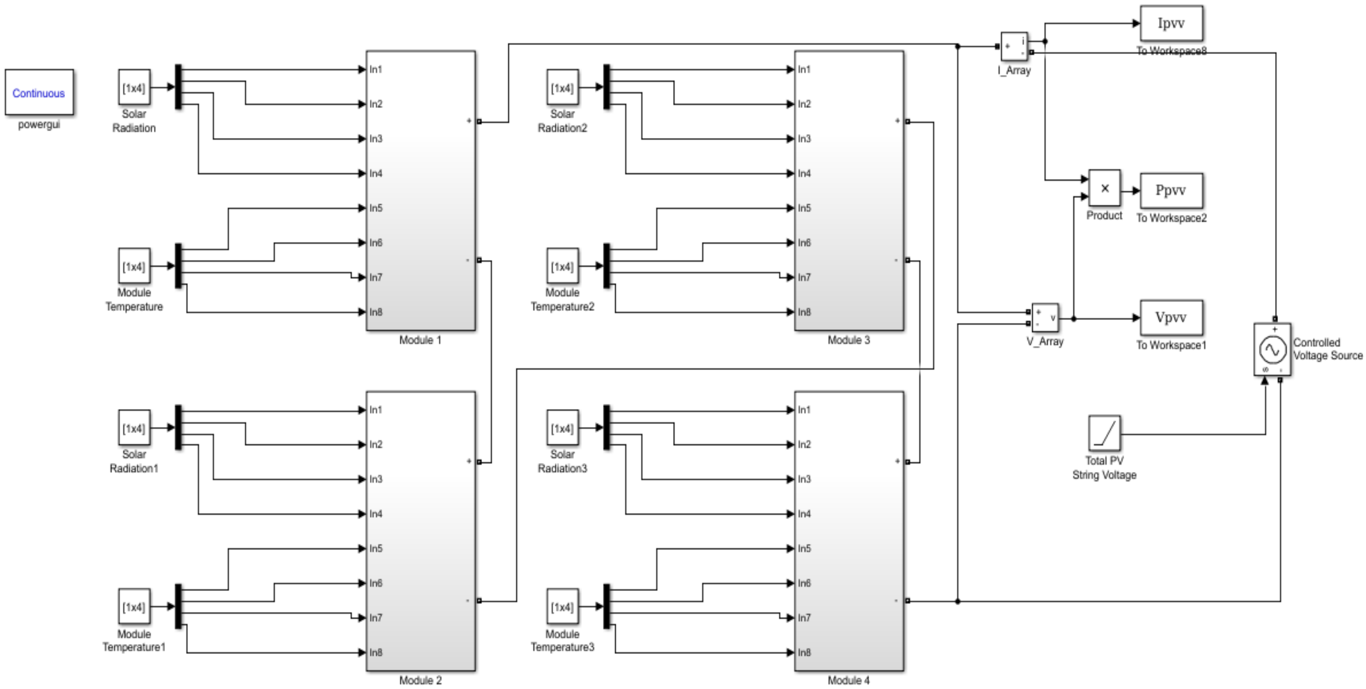


**Fig. 13** PV model for PV array configuration-I

### *4.2. Case I - Constant Cell Temperature with Different Solar Irradiation*

In case 1, the PV modules are operated at different solar irradiation levels such as 1000 W/m$^2$, 800 W/m$^2$, 600 W/m$^2$, and 400 W/m$^2$ respectively, and the respective module numbers are shown in Figure 12 at a cell temperature of 25$^o$C. Since the voltage of the panel is depends on the cell temperature, the current in each panel remains the same. Similarly, the current is depending on the solar irradiation, the voltage in each panel remains the same. As discussed earlier, the manufacturers provide one bypass diode across the panel to protect the PV panel, i.e. SunPower SPR-200-WHT-U panel has at least one bypass diode across it. Figure 14 and Figure 15 shows the I-V and P-V characteristics for all three configurations.

Both the characteristics have relatively high power as discussed earlier with at least one bypass diode. The current and power of all the configurations are increased as solar irradiation changes. The maximum power produced in all the configurations is presented in Table 6. As discussed, the power can be increased ideally by connecting bypass diode across each PV cell, but practically, the model is provided with one bypass diode to improve the power. The configuration-I shows the MPP at 381.2 W; the configuration -II shows the MPP at 503.9 W; whereas the configuration-III shows the MPP at 557.4 W.

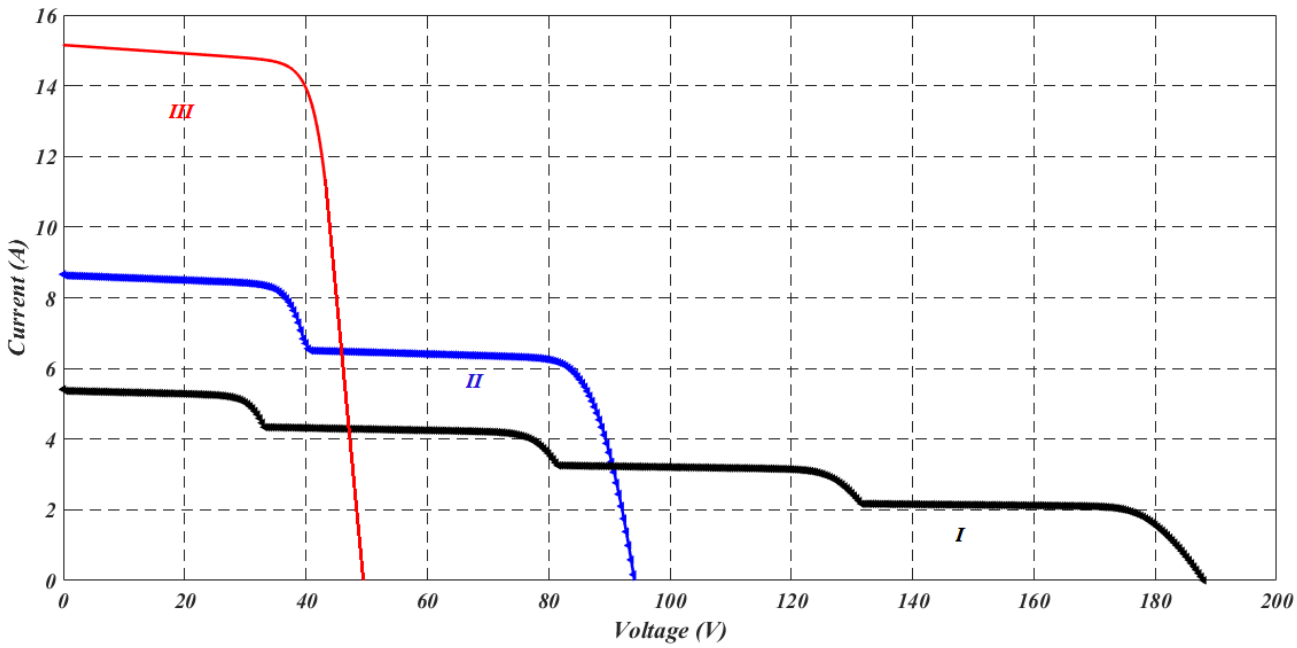


**Fig. 14** Case I – I-V characteristics of three configurations with one bypass diode across each panel

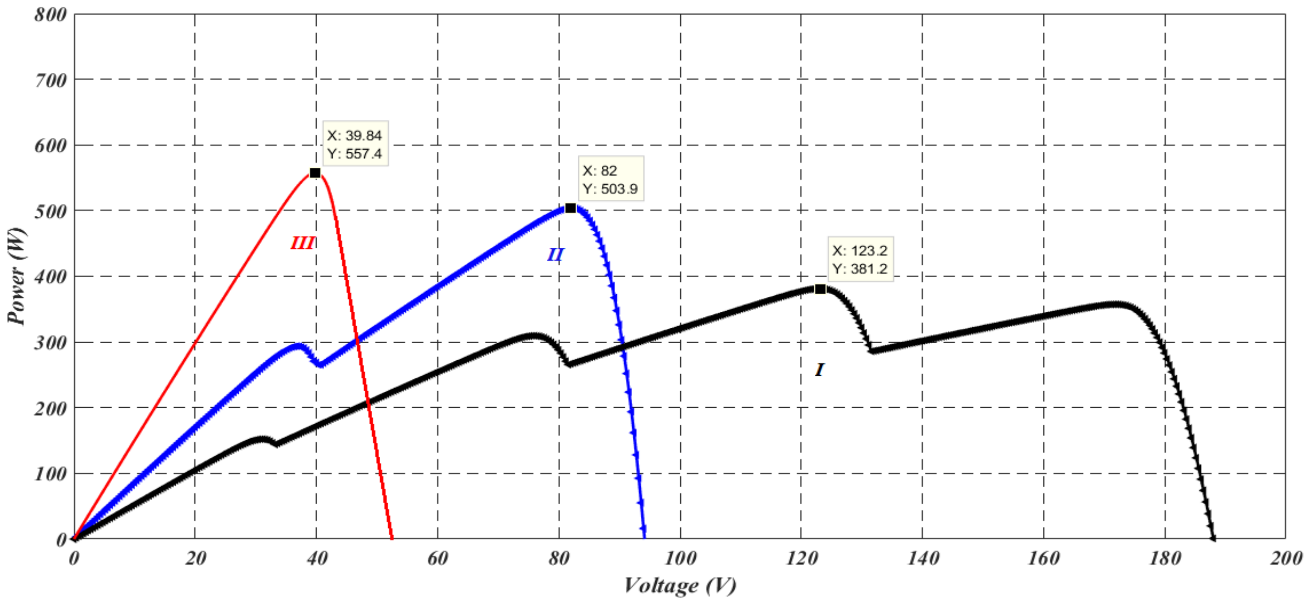


**Fig. 15** Case I – P-V characteristics of three configurations with one bypass diode across each panel

From the Figure 14 and Figure 15, it concluded that the configuration-III is an optimal configuration in terms of high-power production. This is because the current varies rapidly when solar irradiation changes rapidly.

**Table 6**
Case I - Maximum Power Generation from Each Configuration

| No. | Configuration | Maximum Power ($P_{max}$) in Watts | Maximum Voltage ($V_{max}$) in Volts. |
|---|---|---|---|
| 1 | I | 381.2 | 123.2 |
| 2 | II | 503.9 | 82 |
| 3 | III | 557.4 | 39.84 |

### *4.3. Case II - Constant Solar Irradiation with Different Cell Temperature*

In case 2, the PV modules are operated at different cell temperatures such as 45°C, 35°C, 25°C, and 15°C respectively, and the respective module numbers are shown in Figure 12 at constant solar irradiation of 1000 W/m². Since the voltage of the panel is depends on the cell temperature, the current in each panel remains the same. Similarly, the current is depending on the solar irradiation, the voltage in each panel remains the same. Figure 16 and Figure 17 shows the I-V characteristics and P-V characteristics for all three configurations. Both the characteristics have relatively high power as discussed earlier with at least one bypass diode.

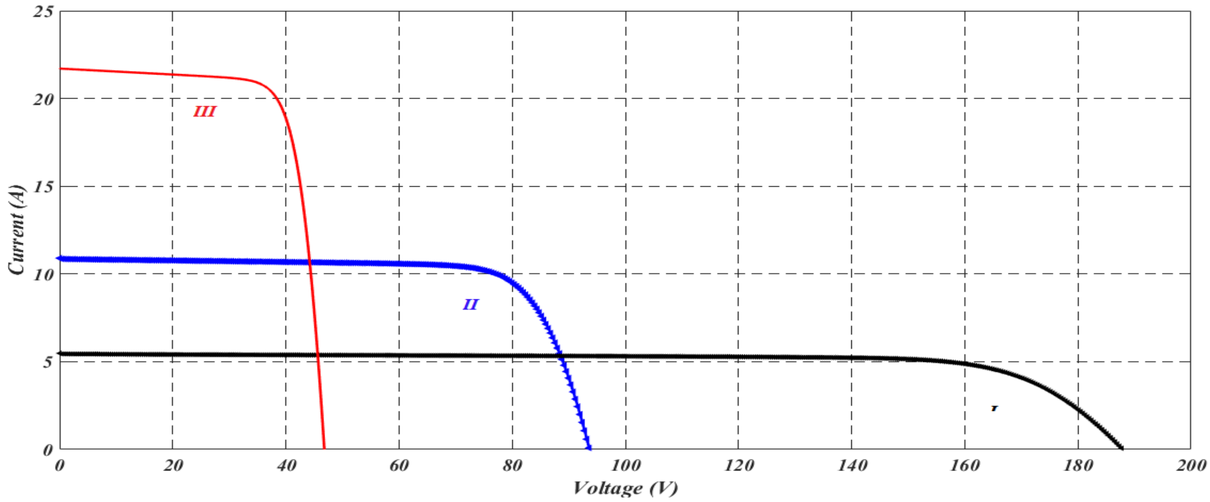

**Fig. 16** Case II – I-V characteristics of three configurations with one bypass diode across each panel

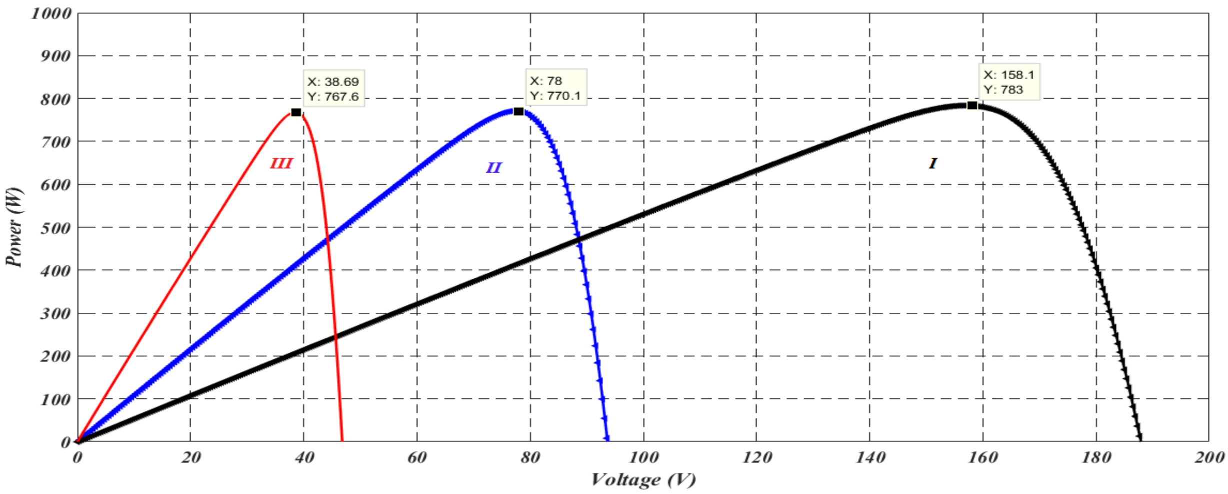

**Fig. 17** Case II – P-V characteristics of three configurations with one bypass diode across each panel

The current and power of all the configurations are increased as solar irradiation changes. The maximum power produced in all the configurations is presented in Table 7. The configuration-I shows the MPP at 783 W; the configuration-II shows the MPP at 770.1 W; whereas the configuration-III shows the MPP at 767.6 W.

**Table 7**
Case-II - Maximum power generation from each configuration

| Configuration | Maximum Power ($P_{max}$) in Watts | Maximum Voltage ($V_{max}$) in Volts. |
|---|---|---|
| I | 783 | 158.1 |
| II | 770.1 | 78 |
| III | 767.6 | 38.69 |

From the Figure 16 and Figure 17, it concluded that the configuration-I is an optimal configuration in terms of high-power production. This is because the voltage varies rapidly when the cell temperature changes rapidly. The configurations-II and III exhibits almost the same power.

### *4.4. Case III - Different Solar Irradiation and Cell Temperature*

In case 3, the PV modules are operated at different cell temperatures such as 45°C, 35°C, 25°C, and 15°C respectively, and different solar irradiation levels such as 1000 W/m$^2$, 900 W/m$^2$, 800 W/m$^2$, and 700 W/m$^2$ respectively. Since the voltage of the panel is depends on the cell temperature, the current in each panel remains the same. Similarly, the current is depending on the solar irradiation, the voltage in each panel remains the same. Figure 18 and Figure 19 shows the I-V characteristics and P-V characteristics for the three configurations with the panels provided with one bypass diode. The maximum power produced in all the configurations is presented in Table 8. The configuration-I shows the MPP at 590.6 W; the configuration-II shows the MPP at 630.8 W; whereas the configuration-III shows the MPP at 649.1 W. From the Figure 18 and Figure 19, it concluded that the configuration-III is an optimal configuration in terms of high-power production. This is because the current/voltage varies rapidly when the solar irradiation/cell temperature changes rapidly.

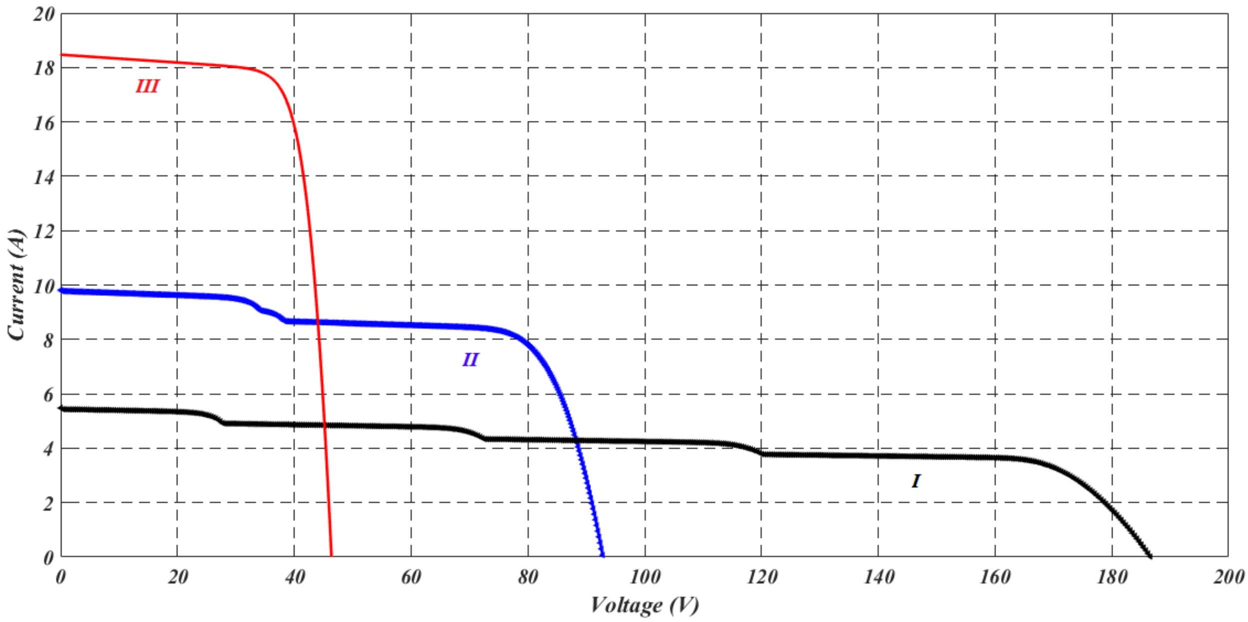


**Fig. 18** Case III – I-V characteristics of three configurations with one bypass diode across each panel

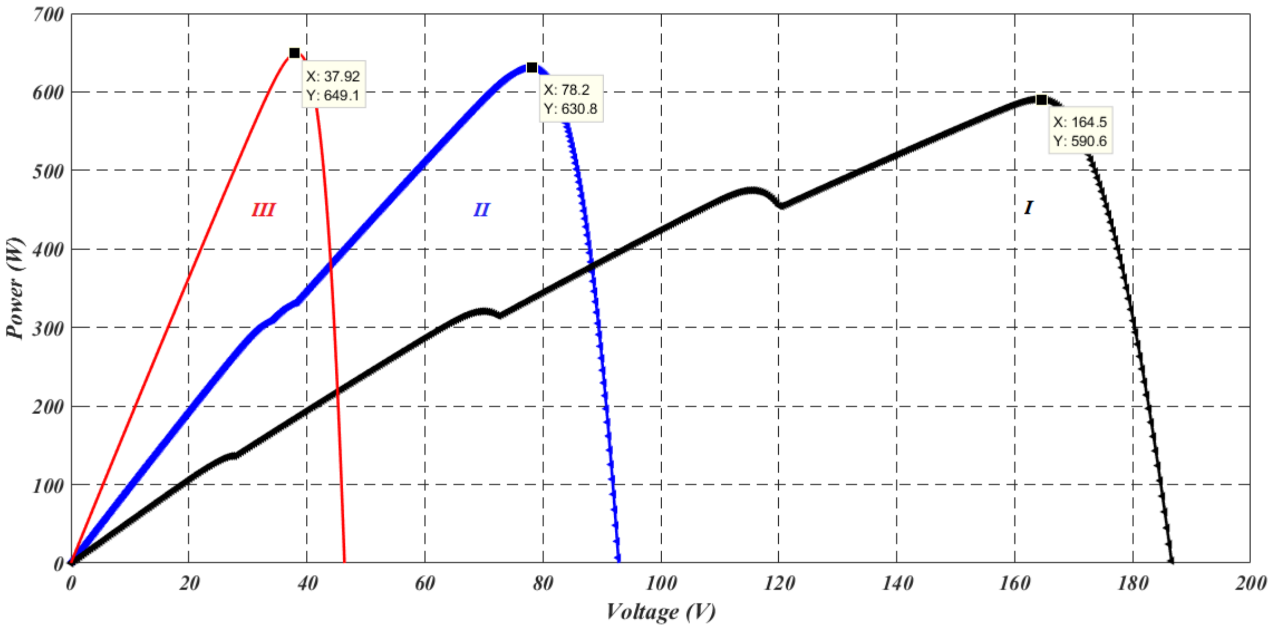


**Fig. 19** Case III – P-V characteristics of three configurations with one bypass diode across each panel

**Table 8**
Case-III - Maximum Power Generation from Each Configuration

| S. No. | Configuration | Maximum Power ($P_{max}$) in Watts | Maximum Voltage ($V_{max}$) in Volts. |
|---|---|---|---|
| 1 | I | 590.6 | 164.5 |
| 2 | II | 630.8 | 78.2 |
| 3 | III | 649.1 | 37.92 |

From the results of all the configurations, the fact is that an addition of bypass diode across the PV module, the I-V characteristics and P-V characteristics exhibit many local MPP and one global MPP. If the bypass diodes connected additionally, both I-V and P-V characteristics show the smooth variation and extract more power from the panel. The derived PV model in this paper is useful to investigate the PV panel under partial or full shading on the PV array. Depends upon the rating/size of the PV array, the total PV unit is divided into many sub-arrays, and it is operating at same operating conditions. The shading effect and different cell temperature effect on the PV cell in large size PV array are not discussed in this paper, but the same can be investigated in Matlab/Simulink. Finally, the optimal cell configuration is derived from the PV model. As solar irradiation is not uniform throughout the day and the PV array, the current contribution from each of the panel is different; if the panels are parallel connected, the different currents results in high power extraction from the PV array. The same concept can be used for analyzing the PV panels, in which the solar irradiation is not uniform throughout the day and throughout the PV panel, the current contribution from each of the PV cell is different; if the few cells are parallel connected, the different currents results in high power from the PV panel. The developed model from Matlab//Simulink can be simulated conveniently for any sized PV panel or PV array. The predicted results from the simulation show the accuracy and reliability on par with the datasheet provided by the manufacturer.

## *5.* Conclusions

The PV cell equivalent circuit and I-V relations including the effects of connecting the panels in series and parallel for the PV array configurations are derived from the single diode and single solar PV cell. The developed PV model can be extended to the PV string, in which the number of cells is connected in series, and it can be extended for the PV array. The main highlight of this paper is that the PV model is derived based on the design data from the manufacture's datasheet. Thus, the model produces accurate output than the in-built PV array model in MATLAB software. The model based on five parameters was developed because the I-V relation is derived for the PV array and this result in cell-panel-array model development. The derived PV model is flexible for all the PV parameters and P-V and I-V for the PV array. The accuracy and reliability of the PV model are verified systematically by comparing the simulation results with data provided by the manufacturers. The developed model requires data from the manufacturer's datasheet. The proposed model features such as reliability, accuracy, and flexibility enable the designers to predict the PV parameters under various operating conditions and this model will be the prediction tool for designers. The PV model can be simulated very easily using Matlab/Simulink simulation software. The accuracy validation of the model was done through a simulation experiment at different solar irradiation and cell temperature for the different configurations. The I-V and P-V characteristics from the predicted results are consistent for all the PV configurations, and the consistent results show the accuracy and reliability of the PV model.

## List of Mathematical Symbols:

$I_{photo}$ - Irradiance current or the photocurrent
$I_{diode}$ - Anti-parallel diode current
$I_p$ - Current through the shunt resistance
q - Electron charge = $1.602\times10^{-19}$ C
n - Diode ideality factor
k - Boltzmann constant = $1.3806503\times10^{-23}$ J/K
$I_o$ - Diode saturation current of the diode
$R_p$ & $R_{se}$ - Shunt and series resistance, respectively
$N_s$ & $N_p$ - Series connected cells and parallel connected PV strings, respectively
$N_{ps}$ - Number of panels connected in series
$N_{pvs}$ - Number of series connected PV cells in each panel
$V_{ar}$ & $I_{ar}$ - PV array's output voltage and the output current, respectively
$T_{ref}$ - PV cell temperature = 298 K or 25°C
$G_{ref}$ - Solar irradiation = 1000 W/m$^2$ at SRC
$I_{photo,ref}$ - Reference photocurrent at SRC
$\alpha'_T$ - Relative temperature coefficient
$\alpha_T$ - Absolute temperature coefficient
$I_{o,ref}$ - Diode saturation current at SRC
$E_g$ - Band gap energy
$T_{amb}$ - Ambient temperature
$T_{NOCT}$ - Cell temperature at normal operating condition
$G_{amb}$ - Solar irradiation at ambient temperature
$G_{NOCT}$ - Solar irradiation at normal operating condition
$U_L$ & $U_{L,NOCT}$ - Heat loss coefficient at the actual operating condition and NOCT, respectively
$\eta_c$ - Cell efficiency
$\tau\alpha$ - Emittance and absorptance product
$\beta_T$ - Open circuit temperature coefficient
$\beta'_T$ - Relative temperature coefficient

## List of Abbreviations:

PV - Photovoltaic
MPP - Maximum Power Point
SRC - Standard Reference Condition
SCC - Short-Circuit Current
NOCT - Nominal Operating Cell Temperature
AM - Air Mass

## Acknowledgments

We extend our thankfulness to GMR Institute of Technology, Rajam, Andhra Pradesh, India, for providing laboratory facility to validate the proposed technique on the PV system at Department of Electrical and Electronics Engineering - Power Electronics Laboratory.

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