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Modelling and simulation of photovoltaic cell in MATLAB

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ABSTRACT

Photovoltaic cell has unique features of harnessing solar energy by absorbing the falling irradiance on its surface and converting it into useful electrical energy. In this study a robust model is built with Tag tools in Simulink environment based on mathematical equations considering all the parameters including shunt and series resistance etc. which affects the performance of the photovoltaic cell. The study shows the variation in irradiance at cell temperature of 25 ^{0}C. The variation in current is also significant from 2A to 7.98A. Additionally at STC, the irradiance of 1000W/m^2 and temperature variation from 25 ^{0}C to 75 ^{0}C shows a significant drop in voltage with insignificant current increment leading to occurrence in power drop.

Key words: *Open circuit voltage, Short circuit current, Photovoltaic cell, MATLAB/Simulink*

Introduction

The free availability of solar energy, advanced conversion technology, and long-term reliability are motivating factors that prompted several countries to determine huge targets for installation of solar photovoltaic power plant within the years to come. In recent past, India also witnessed the fastest development in the solar photovoltaic power generation. India has the geographical advantage of being a tropical country as it receives sun radiation in nearly every part throughout the year that is identical to approximately 3000 hours of sunshine, in power terms, it approximates over 5000 trillion kWh. Almost all parts of India receive solar radiation of about 3.9-7.5 kWh/m^2/day. As of 31stAugust 2020, the country achieved a solar installed capacity of 35,739 Megawatts (MW). The Indian government has set an ambitious goal of achieving a capacity of 1,00,000 MW of solar power generation in the country by 2022.

Solar Photovoltaic (SPV) modules or panels are prepared from semiconductors usually of extrinsic silicon (Si) termed as photovoltaic cell which receive solar radiation as input energy and convert it into electricity directly. Photovoltaic (PV) cells, facilitate the conversion of solar energy directly into electric (DC) power by the photoelectric principle (Martin *et al*., 2017), which can be used to drive electrical loads and can be stored in batteries or fed directly into a power grid. PV systems are gaining popularity because of government initiatives in gradual cost reduction, non-incurrence of any maintenance and running cost technologically and no pollution generation. PV cells works when solar radiations of different wavelength, comprising infrared rays and visible rays, falling on it generates excitons. The density of created excitons depends on the visible rays absorption density at a given point on the PV cell. Researchers (Gruber *et al*., 2005) present methods for

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the optimization of light absorption of organic photoelectric bilayer devices like organic photo detectors and organic solar cells, and investigated the correlation between photo current and the effective absorption area 'A_{eff}' for the whole visible spectrum of the sun. Other challenges posed in the effective utilization of PV cell is its non-linear i–v characteristics due to non-ideality of cell and variation in i-v curves for different levels of insulation and temperature. For a given in solation (k) and temperature (T), there exists unique operating point corresponding to the maximum power point (MPP) and the load line must pass through that operating point of the PV array.

Some researchers (Arora and Hauser, 1982) developed a numerical model of the semiconductor and calculated the output parameters like, short circuit current (Isc), open circuited voltage (Voc), and efficiency of the PV cell considering temperature effect on the material parameters of the cell. AMONIX's high concentration photovoltaic (HCPV) shows decrease in power at the rate of -0.4% per ^{0}C comparative to silicon (poly and crystalline) flat plate PV cells was also reported (Yoon and Garboushian, 1994). a-Sisolar cell of active area 1cm^2 was utilized and the dependence of the current-voltage characteristics on the illumination intensity of simulated light source and temperature were reported (Yoshihiro Hishikawa and Shingo Okamoto, 1994). Various researchers (Gwandu and Creasey, 1995, Youichi Hirata and Tatsuo Tani, 1995 and Youichi Hirata *et al.*, 1998) also reported that the environmental factors such as irradiance, cell temperature and spectral solar radiation affect the seasonal variation in photovoltaic (PV) module conversion efficiency.The hetero module, c-Si module, and p-Si module with temperature coefficient values of -0.3%/ ^{o}C, -0.4%/ ^{o}C and-0.4%/ ^{o}C, respectively were used (Nishioka and Hatayama, 2003) and evaluated under the standard test conditions and reported that improvement in every 0.1%/ ^{o}C temperature coefficient of cell leads to 1% increase in PV module output.

The moisture ingresses from the edges of the encapsulated PV module by highly diffusive and soluble ethylene-vinyl acetate EVA(67 wt % ethylene and 33 wt % vinyl acetate) used to protect the photovoltaic modules from environmental exposure. Kempe (2006) studied the high diffusivity and solubility of EVA and concluded that in a life time of 25-30 years the moisture definitely causes adverse effect on the performance of PV module. Some researchers.

In recent past, many researchers have done mathematical modeling of PV module using different types of software such as C-programming, Excel, Matlab, Simulink, or the toolboxes they developed. A model in MATLAB environment was developed to study the effect of temperature, solar irradiation, diode quality factor and series resistance (Walker, 2001 and Gonzalez-Longatt, 2005). A combination of Matlab m-file and C-language programming was utilized to model the PV module (Gow and Manning, 1999). All these methods require knowledge of some programming language. Many researchers (Salmi *et al.,* 2012; Panwar and Saini, 2012; Savita Nema and Agnihotri, 2010 and Sudeepika and Khan, 2014) investigated the effect of solar insolation and temperature, and physical parameters such as diode's quality factor, series resistance (R_s), shunt resistance (R_{sh}), and saturation current, based on solar cell and array's mathematical equations and built with common blocks in Simulink environment. But these authors did not explain the procedure for the readers.

To establish the mathematical model of a PV cell, the physical nature of cell behavior such as diode's quality factor, series resistance (R_s), shunt resistance (R_{sh}), and saturation current are necessary because the data sheets provided by the manufacturer don't contain these details. However, the information provided by the manufacturer cannot be ignored. The nonlinear i-v curve of a PV cell is simulated by an equation comprising multiple parameters; those provided by manufacturer are known as constant and some of course must be computed. Sometimes, researchers develop simplified methods where some unknown parameters cannot be calculated, and they are thus assumed constant. Walker (Walker, 2001) in their study included the series resistance (R_S) but ignored the parallel resistance for a model of moderate complexity. The same assumption is adopted (Benmessaoud *et al.,* 2010); Atlas and Sharaf, 1992; Bryan, 1999; Bouzid *et al.,* 2005) by considering the parallel resistance as very large. Other authors (Townsend, 1989), Alsayid and Jallad, 2011; Kashif Ishaque and Syafaruddin, 2011; Gazoli *et al.,* 2009; De Soto, 2006 and Chouder *et al.,* 2012) neglect both parallel and series resistances considering them being very large and very small, respectively. However, there are other studies which considered that these two internal characteristics of the PV module are very significant and according to the researchers, two or three other parameters; the photo current (I_{ph}), the saturation current (I_0) and the ideality factor (A) and must be determined more accurately.

It is evident from above that different methods used by various researchers have their own merits and demerits and are not sufficient to study all parameters which i-v and p-v characteristics of PV cell define significantly. Therefore, the study proposes a robust model built with Tag tools in Simulink environment. The proposed model shows strength in investigating all parameters' influence on solar PV array's operation. In addition, a unique step-by-step modeling procedure shown allows readers to follow and simulate by themselves to do research.

Mathematical Equivalent Circuit of PV cell

An ideal equivalent circuit for a photovoltaic cell is shown in Fig. 1.

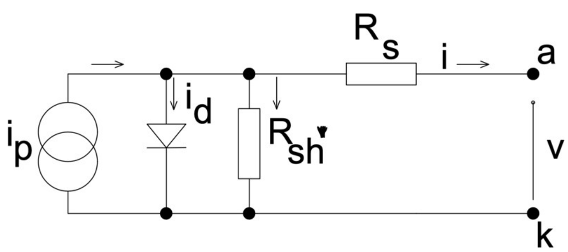

Fig. 1(a). PV Cell Equivalent Circuit

Fig.1(a) shows a PV-cell circuit having a combination of generator (I_p generated inphoton), dissipater (I_d dissipated in diode) and shunt resistance in parallel (R_{sh}) and impedance (R_S) in series. All these above parameter combined makes a PV-cell and its equivalent circuit is shown in Fig.1(b).

Now we will try to generate equation for the terminal current w.r.t. various parameters of PV-cell,which will be useful for selection/choice of the PV-cell.

From Fig.1(a);

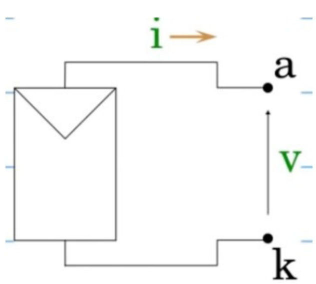

Fig. 1(b). PV Cell Symbol

Photo Current $5p_{55}$

$5<_{5]!}=5<_{57}+5<_{5'!}+5<$ .. (1)

where,

I=Terminal Current

I_D=Current thorough Diode

I_{sh}=Current thorough Shunt Resistance

Voltage at terminala: '$5I+5<.5E_{5}$`'

Shunt Current 'I_{sh}' flowing through shunt resistance 'R_{sh}' is given as

$$I_{sh} = \left(\frac{V+I\,R_s}{R_{sh}}\right) \quad .. (2)$$

From P-N junction theory the current through diode 'I_D' will be equal to

$$I_D = I_0\left(\exp\left(\frac{V+I\,R_s}{n.\,V_T}\right)\right) \quad .. (3)$$

Where,

n =2 for silicon (It is a material property parameter)

V_T =Volt equivalent temperature

$$V_T = \left(\frac{K\ (Boltzman\ constant)\ X\ T}{Q\ (Charge\ in\ coulomb)}\right)$$

Substituting the value of K and Q, we get

$$V_T = \left(\frac{T}{11600}\right)$$

Reverse Saturation Current (I_D)

It is dependent on material and doping and also temperature, Given by equation

$$I_0 = K.T.m\left(exp\left(\frac{-E_{GO}}{n.\ V_T}\right)\right)$$

Where;

K, is constant depending on the dimension of the P-N junction and material property

E_{GO} = numerically equivalent band gap energy in electron volt (eV), it varies between 1.16 to 1.21, depend on grade of purification, solar grade for PV-cell is more equal to 1.16 volts.

T = temperature (K)

m = 1.5 for silicon

Equation (1) can be written as, for terminal current 'I'

$I = I_{ph} - I_D - I_{sh}$ .. (4)

Substituting the values of I_{sh}, & I_D from eq. (2), (3) in eq (4), we get

$$I = I_{ph} - I_0\left\{\exp\left(\frac{V+IR_s}{n.V_T}\right) - 1\right\} - \left(\frac{V+IR_s}{R_{sh}}\right) \quad .. (5)$$

The reverse saturation current 'I_0' of a PV cell depend upon the material and doping of P-N junction and also depends on temperature.

I-V and P-V curves of an typical PV cell

The operating point of a PV cell/array under constant irradiance and cell temperature is the intersection point of the I-V characteristics and the load characteristics, marked as point '3' as shown in Fig. 2. An imaginary straight line starting from origin and passes through point '3' with gradient M=1/R=I/V represents the load characteristic. The system operating point moves along the I-V characteristic curve, from point '1' to '2', as load resistance increases from zero to infinity. The MPP is at '3', where the area (equivalent to output power) under the I-V characteristic curve is maxima. For too-high load resistances, the operating points lie in the '3-2' region. For too-low load resistances, the operating points lie in the '3-1' region. MPP can thus be obtained by matching load resistance to PV cell/array characteristics.

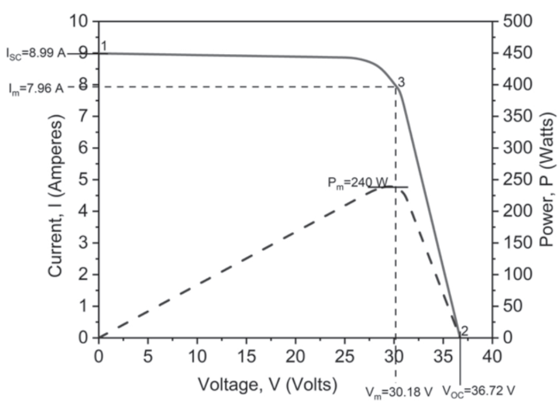

Fig. 2. I-V and P-V curves of PV cell

In above V-I characteristic curve of a PV cell, there are three significant points i.e. point '1' a short circuit point, point '2' an open circuit point and point '3' as maximum power point (MPP) are marked. These three points are very important and are a part of manufacturer data sheet of any given PV cell or module. It helps to predict the performance of the system. The significance of these points are explained below.

<u>Point 1</u>: Short Circuit current Point

This point is known as short circuit because when current axis intercept at voltage axis at origin, then V=0 and at point 1 the current 'I' is termed as short circuit current and designated by 'I_{SC}'. On PV-Cell circuit (Fig. 1(a)) the circuit is short circuited at terminal 'a' and 'k' then the voltage in circuit dropped to zero and current rise to its maximum value. In such condition the maximum value of terminal current 'I' is re designated as short circuit current '' and it will be written as

$$I = I_{sc} \qquad V = 0$$

Apply these constraints to terminal current Eq. 5, we get

$$I_{sc} = I_{ph} - I_0\left\{\exp\left(\frac{0+I_{sc}R_s}{n.V_T}\right) - 1\right\} - \left(\frac{0+I_{sc}R_s}{R_{sh}}\right) \quad .. (6)$$

Further constraints are: $R_S <<< R_{sh}$ and hence following to conditions arises:

Condition 1

The term 'I_{SC} R_S' is very negligible in comparison to R_{sh} and hence term '2' i.e. $\left(\frac{0+I_{sc}R_s}{R_{sh}}\right)$ of equation (6) is neglected

Condition 2

The term $(0 + I_{sc}R_s/n.V_t)$ of equation (6) tends to zero and hence neglected
On applying conditions (1) & (2) the equation (6) reduces to

$$I_{sc} = I_{ph} \quad .. (7)$$

We know that the photo current is directly proportional to the solar irradiaitons i.e. as the magnitude of falling solar irradiations on the surface of PV cell result into the generation of equal amount of photo current. Further, It is evident from Eq.(7) that the photo current is directly proportional to short circuit current of a PV cell, hence under the given conditions of solar irradiations if PV-cell is short circuited, it gives maximum current equivalent to I_{ph} and that current is termed as short circuit current and designated by I_{sc}.

<u>Point 2</u>: Open circuit voltage point

It is the point where current (I =0) is zero and voltage so obtained is termed as open circuit voltage 'V_{OC}'. It is obtained when no external load is connected across terminal 'a' and 'k' in 1(a). On applying the above constraints then the current 'I' and voltage 'V' across terminal 'a' and 'k' become zero and open circuit voltage (V_{OC}) and expressed as

$$I = O \qquad V = V_{oc}$$

On apply above constraints to eq.5, we get

$$0 = I_{ph} - I_0\left\{\exp\left(\frac{V_{oc}+0}{n.V_T}\right) - 1\right\} - \left(\frac{V_{oc}+0}{R_{sh}}\right) \quad .. (8)$$

Further constraints are: R_{sh} >>>>>V_{oc} and hence term (V_{oc} + $0/R_{sh}$) may be neglected and Eq (8) reduce to

$$0 = I_{ph} - I_0\left\{\exp\left(\frac{V_{oc}+0}{n.V_T}\right) - 1\right\}$$

$$I_{ph} = I_0\left\{\exp\left(\frac{V_{oc}+0}{n.V_T}\right) - 1\right\}$$

Taking log both side, we get

$$\log_e I_{ph} = \log_e I_0\left(\frac{V_{oc}}{n.V_T}\right) - \log_e I_0$$

Multiplying both side by '$n.V_T$' and we get

$$(V_{oc}) = n.V_T \log_e\left(\frac{I_{ph}+I_0}{I_0}\right) \quad .. (10)$$

It is evident from above Eq.(10) that the open circuit voltage 'V_{oc}' like short circuit current is directly proportional to the photo current 'I_{ph}' but in logarithmic way. Therefore, when solar insolation changes then 'V_{oc}' changes in logarithmic way. Eq.(7) also shows that the short circuit current 'I_{SC}' is also directly proportional to insolation, but it changes linearly with insolation

<u>Point 3</u>: Maximum Power, P_M

Third significant point on the V-I and P-V curve is maximum power point (MPP). To get point '3' let us assume the voltage axis is same and at origin both V and I are zero. But between origin and V_{OC} there will be some maximum point for power because *P= V.I.* So, when we draw a power curve, we will get some hill-top point for 'P_M' as shown in Fig.2. The peak of this curve is designated by 'P_M' a point of maximum power.

If we extend the peak of 'P_M' vertically it coincides with V-I characteristic curve and from the point of coincidence a horizontal intersect at y-axis. The current and voltage so obtained at the point of intersection is called maximum current 'I_M' and maximum voltage 'V_M'. This point helps in selecting the PV-cell for particular application.

Reference Model

The 175 W photovoltaic module is taken as the reference module for simulation and the detailed parameters of the module is given in Appendix-A (Table 1A). A mathematical model of photovoltaic module including fundamental components of diode, current source, series and parallel resistance is modelled with tags in Simulink. The simulation of photovoltaic module of 175 W is based on the equations and stepwise procedure is given below;

<u>Step-I</u>

The input parameters used in the modelling are displayed in the Table 2A.

The simulation of PV cell in Simulink is done on the basis of the following mathematical equations:

Saturation Current, I_0

$$I_0 = I_{rs}\left(\frac{T}{T_n}\right)^3 e\left[\frac{q \times E_{g_0}(\frac{1}{T_n} - \frac{1}{T})}{n \times k}\right]$$

Reverse Saturation Current, I_{rs}

$$I_{rs} = \frac{I_{sc}}{e\left[\frac{q \times V_{oc}}{n \times N_s \times k \times T}\right] - 1}$$

Shunt Current, I_{sh}

$$I_{sh} = \frac{V + IR_s}{R_{sh}}$$

Photo Current, I_{ph}

$$I_{ph} = I_{sc} + K_i(T - 298)\frac{G}{1000}$$

Terminal Current, I

$$I = I_{ph} - I_0\left[e\left(\frac{q(V + IR_s)}{n \times k \times N_s \times T}\right) - 1\right] - I_{sh}$$

Simulink simulation of saturation current equation

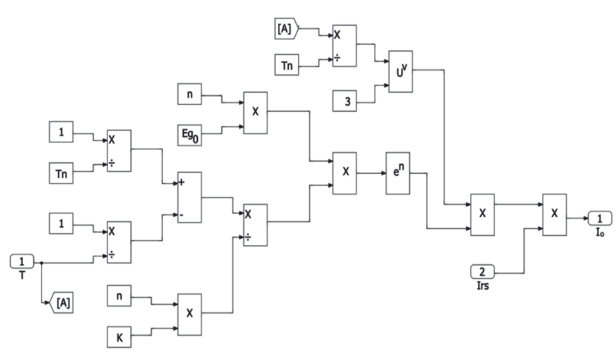

Fig. 3. Saturation current equation modelled in Simulink

Simulink Simulation of Reverse Saturation Current

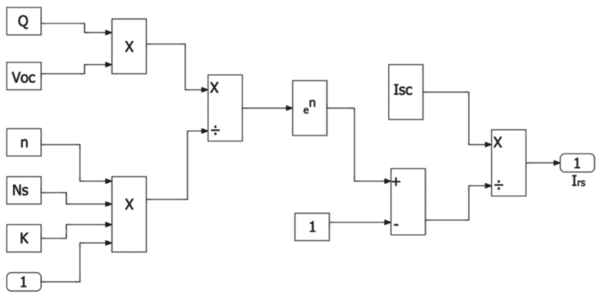

Fig. 4. Reverse saturation current equation modelled in Simulink

Simulink Simulation of Shunt Current

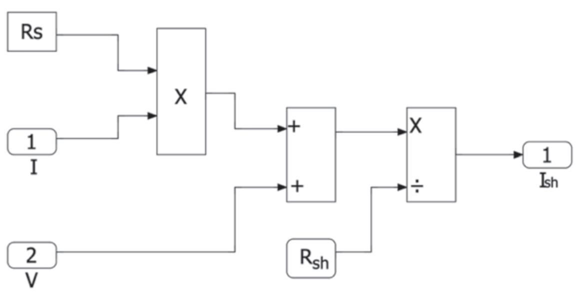

Fig. 5. Shunt current equation modelled in Simulink

Simulink Simulation of Photo Current

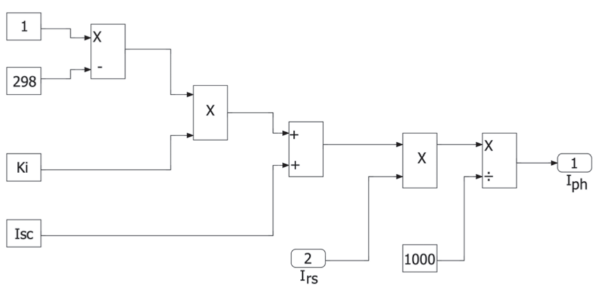

Fig. 6. Photo current equation modelled in Simulink

Simulink Simulation of Terminal Current

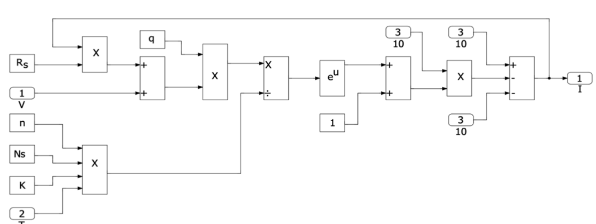

Fig. 7. Terminal current equation modelled in Simulink

The various parameters of photovoltaic cell/module and their input and output variables are summarised in Table1 below:

Table 1. Details of PV cell parameters

S.No.	Parameters	Input	Output
1	Saturation Current, I_0	T	I_0
2	Reverse Saturation Current, I_{rs}	T	I_{rs}
3	Shunt Current, I_{sh}	I, V	I_{sh}
4	Photo Current, I_{ph}	T, G	I_{ph}
5	Terminal Current, I	T, V	I, I_0, I_{sh}, I_{ph}

Simulation of I-V curves and P-V curves

The electro-physical output rating of PV modules are given at specific environmental conditions (1000W/m^2 Global radiations, 25 °C cell temperature and 1.5 Air Mass). These conditions are called Standard Test Conditions (STC). The manufacturer specify the values of short-circuit current I_{sc}, open-circuit voltage V_{oc} and maximum-point power (MPP) under STC for PV modules to ±10% tolerance. Realistically, these standard test conditions occur very rarely; however, if the sun shines with the specified intensity, then, cell temperature will be higher than 25 °C.

I-V curves and P-V curves were simulated for various irradiances and temperatures by using MATLAB Simulink. The PV module characteristic parameters were chosen from a standard module and are summarised in Table 1A (Appendix-A), as it is one of the types to be used in the experimental prototype.

In Fig. 8, it shows PV module that was modelled and simulated in MATLAB/Simulink for variable irradiance and constant temperature 25 ^{0}C. This model comprised the blocks that were developed

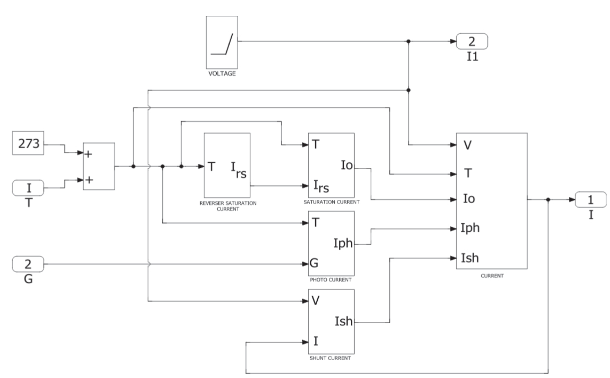

Fig. 8. PV module modelled in Simulink for variable irradiance and temperature

from equations of Saturation Current, I_0, Reverse Saturation Current, I_{RS}, Shunt Current, I_{sh}, Photo Current, I_{ph}, and Terminal Current, I. Fig.8 depicts PV modelled module in MATLAB/Simulink on the effect of the temperature.

Results and Discussion

Fig. 9(a) shows the PV module's I-V curve for various irradiances at constant temperature. The irradiance ranged from 200W/m^2 to 1000W/m^2 while temperature was maintained at 25 °C. As the irradiance increased, the current increased. Voltage, on the other hand, remained relatively constant throughout the irradiance range. Fig. 9(b) shows the PV module's P-V curved for various irradiances and 25 °C constant temperatures.

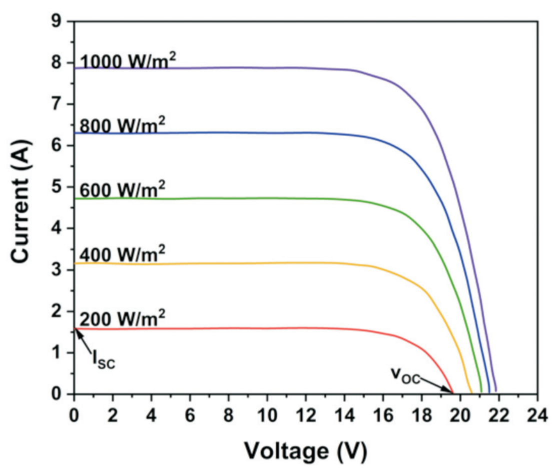

Fig. 9(a). PV module's I-V curves for various irradiance and 25^{0}C temperature

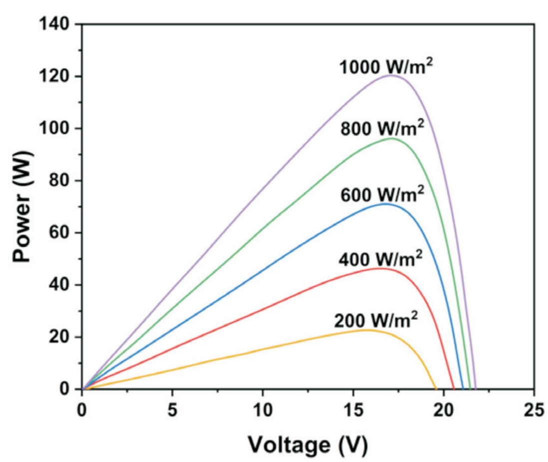

Fig. 9(b). PV module's P-V curves for various irradiance and 25^{0}Ctemperature

Fig. 10(a) shows the module's I-V curved for various temperatures and 1000W/m^2 constant irradiance. The temperature ranged from 25 °C to 75 °C. The performance of the module was noted to be best at 25 °C and 1000W/m^2 irradiance. Fig. 10(b) shows the P-V curved for various module temperatures at 1000W/m^2 constant irradiance.

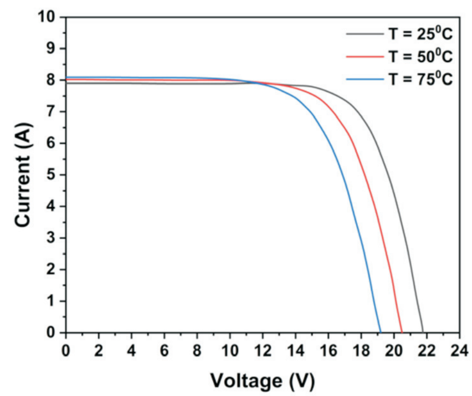

Fig. 10(a). PV module's I-V curves for various temperatures and 1000 W/m^2 irradiance

From the two Fig. 10 (a) & (b), it is noted that lower the temperature higher the maximum power is and the larger the open circuit voltage is. On the other hand, a lower temperature gave a slightly lower short circuit current.

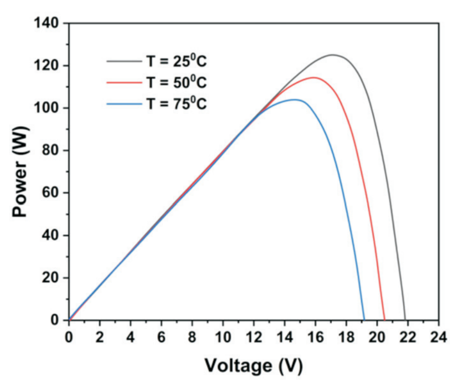

Fig. 10(b). PV module's P-V curves for various temperatures and 1000 W/m^2 irradiance

Conclusion

An accurate single diode photovoltaic cell/module electrical model was presented and demonstrated in Simulink/MATLAB for a typical solar panel whose characteristics are displayed in Table 1A (Appendix-A). The proposed modelling method avoided complexities involved in PV parameter identification

Appendix - A

Table 1A. Specifications of PV Module

S.No.	Specifications	Value
1	Open circuit voltage, V_{oc}	21.9V
2	Short circuit current, Isc	7.98A
3	Maximum power voltage, V_{mp}	19.3V
4	Maximum power current, I_{mp}	6.22A
5	Maximum power rating, P_{max}	175W
6	Maximum system voltage	600V
7	Temp. coefficient for current	0.001904
8	Temp. coefficient for voltage	-0.28
9	Temp. coefficient for power	-0.23
10	Normal operating cell temperature (NOCT)	75
11	Number of cell	36

Table 2A. Input parameters for a cell

Parameters	Value
Nominal temperature, T_n	298 K
Ideality factor, n	1.2
Boltzman constant, K	1.3805×10^{-23} J/K
Electron charge, Q	1.6×10^{-19} coulomb
Band gap energy, E_{go}	1.1 eV
Open circuit voltage, V_{oc}	0.6 V
Short circuit current, I_{sc}	7.98 A
Series resistance, R_s	0.0001
Shunt resistance, R_{sh}	1000

while achieving comparable accuracy. The method was easy to implement in various simulation platforms for PV power systems studies.

Simulation results shows that the solar irradiance (G) and cell/module temperature are the only input variable which effects the performance of the solar cell. The results shows that:

1. The I-V curves at constant cell temperature of 25 °C and variable solar irradiance ranging from 200 w/m^2 to 1100 w/m^2 and varied at an increment of 100 w/m^2 shows that the short circuit current changes from 2A to 9A and variation in open circuit voltage is not so significant.
2. The P-V curve also shows that at standard cell temperature of 25 °C the power output increases significantly with the increase in solar irradiance.
3. At standard test radiations of 1000 w/m^2 the temperature rise from 25 °C to 75 °C at an interval of 25 °C shows that the drop in open circuit voltage in significant from 21.8V to 18.5V.
4. The rise in cell temperature at constant radiations the rise in current is nominal and hence resulting power output reduces considerably.

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