Modeling of PV cell, PV Module, PV array and PV IV characteristics analysis using MATLAB/SIMULINK

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Abstract

In this paper, a study of modeling PV cell (solar cell), PV module (solar module) and PV array solar array) using Matlab/Simulink software is presented. This study is focused on the study to design photovoltaic cell, photovoltaic module, photovoltaic panel and PV array (solar array) and to analyze the change of PV performance according to change of different parameters such temperature, solar irradiation, reverse saturation current, series resistance and shunt resistance. This study shows the PV and IV characteristics curve for each model from which MPP (maximum power point) is determined. In this study, for different PV and IV characteristic curves are gained for varying temperature with specified solar irradiation condition and then the MPP is tracked. The highest power output is also compared between the designed PV module and the selected PV module (MX Solar USA MX60-245).

Keywords

photovoltaic cell, photovoltaic module, photovoltaic panel, photovoltaic array, current-voltage (I-V) characteristic curve, power-voltage (P-V) characteristic curve.

1. Introduction

In the present condition, the dependence on fossil fuels to get energy becomes the main threat for global warming. Using of fossil fuels to get energy may cause water pollution, oil exudes, water table poisoning from fracking, air pollution, mercury emission, acid rain, ozone layer depletion [1]. The environment is polluted and human health is affected badly by the increasing amount of use of fossil fuels [2]. And the main disadvantage of fossil fuels is that these energy sources are not renewable. The day when the fossil fuels are depleted totally is very near. At this situation the only way to continue the supply of energy is to research for utilizing the renewable energy sources to fulfill the requirement of energy. The sun is considered as a main renewable energy source as the solar energy does not deplete any time and for consistency of energy supply. It does not reduce any natural sources and does not cause any CO_2 emission. Using of sun as a renewable energy source is environment friendly and it also does not cause any harm to human health compared to fossil fuels. The main advantages of using solar energy are – reclamation of degraded land, no emission of greenhouse or toxic gases (CO_2, NO_x, SO_2), enhance the local energy independence, acceleration of electrification in rural areas [3]. There are many characteristics in solar energy for which the sun can be considered as the primary energy source.

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The uses of Photovoltaic (PV) has emerged in last few decades as power generation process from solar energy, which is the main renewable energy source. Photovoltaic system has the merits of lower maintenance, no wear as well as tear and it has no risk of gas emission [4]. The main operations of photovoltaic mechanisms are in either stand-alone system like- domestic and electric lightening, water pumping, stream flow gages, remote guard posts, temporary traffic signs [5]

This paper focuses on modeling a strategy for forecasting the current-voltage and power-voltage properties of solar arrays, which is becoming increasingly important due to the growing importance to accelerate the efficacy of photovoltaic system. It may be used to look at the effects of temperature and insolation changes on PV characteristics, as well as the impact of array configuration. The MATLAB environment was used to generate the block diagrams and run simulation. A notable contribution of this study is the use of the electrical circuit model as the simulation's main engine. This study uses a single diode instead of a two-diode model due to the huge increase in processing time in a two-diode system [6].

The main purpose and aim of this study is to provide the fundamental as well as conceptual knowledges on design of the photovoltaic cell (solar cell), photovoltaic module (solar module), photovoltaic panel (solar panel) and photovoltaic array (solar array) using Matlab / Simulink software and examine the impact of various parameters on PV cell. The effects of various parameters such operating temperature, solar irradiation, reverse saturation current, shunt resistance and series resistance on the output current(I) and voltage(V) from PV cell are discussed in this paper. And the characteristics curves (IV and PV) are also achieved by simulating each model in Matlab /Simulink.

2. Electrical Circuit Model Of the PV

The identical circuit diagram of a photovoltaic panel is presented in fig. 1. This circuit is structured with one diode, one current source, one shunt resistor and one series resistor.

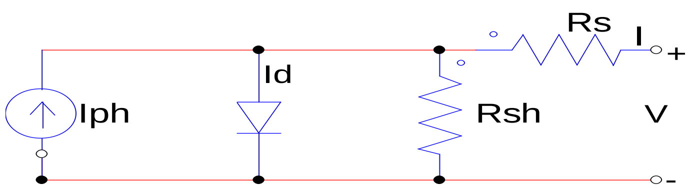

Fig.1 Electrical circuit model of PV cell using PSIM software

Based on the circuit, the current(I) that is generated from the photovoltaic panel can be presented by the equation below-

$$I = I_{ph} - I_s\left(exp\frac{q(V+R_sI)}{NKT} - 1\right) - \frac{(V+R_sI)}{R_{sh}} \dots\dots\dots (1)$$

$$I_{ph} = \left(I_{sc} + K_i(T-298)\right)\frac{\beta}{1000} \dots\dots\dots (2)$$

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$$I_0 = \frac{I_{sc} + K_i(T - 298)}{\exp\left(\frac{q\left(V + K_v(T - 298)\right)}{aKTN_s}\right) - 1} \ldots \ldots \ldots (3)$$

I_0, I_{ph}, I_s, I_{sc}, N_s, V_m, I_m, T, a, K, q, β, R_s and R_{sh} represents the saturation current inverse of the diode, the photo current, reverse saturation current, the short circuit current, the cell number connected in series, the voltage at the module terminals, the module current, the temperature ambient in K, the ideality factor, the charge of the electron, solar irradiation, series and shunt resistances respectively.

3. Characteristics and Process of operation of a PV cell

3.1. Characteristics of a PV cell

The power-voltage (P-V) characteristic curve and current-voltage (I-V) characteristic curve are the plots which are achieved for all possible points in a considered working range. A maximum power point (MPP) exists in one exact point on each curve.

$$P_{mpp} = I_{mp} V_{mp}$$

I_{mp} and V_{mp} can be obtained from the maximum point of a characteristic curve. And the other parameters of PV cell are open circuit voltage, short circuit current, fill factor and efficiency.

3.1.1 Open Circuit Voltage presents the content of voltage when the circuit remains open in PV cell and the current passing through the cell is equals to zero.

$$V(at\ I = 0) = V_{oc}$$

When the current is zero, the highest voltage in a photovoltaic cell can be produced which is presented as the open-circuit voltage (V_{oc}). The forward bias on the solar cell which is created by the preference of the photovoltaic cell connection with the light-generated current and this forward bias is represented by the open circuit voltage.

$$V_{oc} = \frac{NKT}{q} \ln\left[\frac{I_L}{I_0} + 1\right]$$

Here,

N= Ideality factor

I_L= Light generated current

T= Temperature

I_0= Dark saturation current.

K= Boltzmann constant

q= Charge of electron

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From the equation above, temperature and open circuit voltage (V_{OC}) are directly proportional. As a result, V_{OC} rises in direct proportion to temperature. However, this is not happened. Because as the temperature rises, the saturation current increases rapidly. As a result, determining the impact of temperature on open circuit voltage is challenging. It decreases as the saturation current varies with temperature.

3.1.2. Short Circuit Current (I_{sc}) is obtained as the maximum output current from photovoltaic cell that occurs at the time when zero voltage is found across the system.

$$I(at\ V = 0) = I_{sc}$$

The short-circuit current is generated by creating and building up of light-generated carriers. In a perfect solar cell with negligible resistive loss mechanisms, there's no difference between the light-generated current (I_L) and the short-circuit current (I_{sc}). As a result, the short-circuit current is the maximal amount of current that can be extracted from a photovoltaic cell.

3.1.3 Fill Factor

The quality of a photovoltaic cell can be measured by obtaining the fill factor (FF). It's computed by comparing the highest power to the conceptual power produced by multiplying short circuit current and open circuit voltage.

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}} = \frac{P_{max}}{I_{sc}V_{oc}}$$

The fill factor (FF) can specify an organic solar cell's power conversion efficiency. There are different factors that might have a large impact on fill factor, and these elements interact in a complex way. As a result, it is challenging to understand the concept of fill factor. The scientific progress should be examined in understanding FF in organic solar cells depending on the three major parts in the photovoltaic cell equivalent circuit which are diode, shunt resistance and series resistance.

3.1.4 Efficiency is determined from the comparison of the maximum output power to the input power.

$$\eta = \frac{P_m}{P_{in}} \times 100$$

The efficiency of a PV cell is a major parameter which is used to compare its performance to another photovoltaic cell. The efficiency of a photovoltaic cell can be determined by comparing the output and input energy. Photovoltaic cell efficiency can be affected by the operating temperature of the photovoltaic cell, the band spectrum and intensity of sunlight.

3.2 Process of operation of a PV cell

Solar energy which comes from sunlight can be altered into direct current (DC) by operating a photovoltaic cell. Semiconductor materials are widely used to create photovoltaic panels and the most commonly used material is silicon to make photovoltaic panels. PV cells can be assembled in series to get higher output voltage as well as to get higher output current PV cells can be assembled in parallel [7].

The operating system of a PV cell can be described using a P-N junction with diffusion and draft currents for direct and reverse polarization respectively. P-type silicon and n-type silicon are two types of semiconductors which are most used in solar cells. P-type silicon is made by mixing with elements which have one fewer electron than silicon in the outer region of their energy level, such as gallium or boron. As a result, a space with electron emptiness or "hole" is generated as boron has one less electron than the number of electrons which is needed to generate bonds with the atoms of silicon around it. On the other side, phosphorus atoms, for example, contain one extra electron than silicon in their outer region of their energy level resulting in n-type silicon. The outer energy level of phosphorus contains five electrons. Phosphorous forms connections with neighboring silicon, only one electron is participated in the bond creating process. Instead in the silicon framework, it roams freely. A photovoltaic cell includes a p-type layer and two n-type layers of silicon. And the p-type layer is sandwiched between the n-type layers. The n-type layer has too much electrons whereas there are too many holes which have positive charge in the p-type layer. Near the intersection portion of these layers, electrons of the n-type junction enter into the holes of the p-type junction. As a result, the holes are filled with the electrons in the depletion zone (attenuation region) surrounding the linked zone. After this, the holes in the attenuation zones becomes loaded with electrons, the n-type layer (at first, electrons present here) of the depletion zone contains positive ions and the p-type layer (at first, holes present here) contains ions which are negatively charged.

When solar irradiation occurs on a photovoltaic cell, the silicon releases electron that causes the composition of gaps or holes. And when it happens, the electric field transfer electrons to the n-type side and holes to the p-type side. When the p-type and n-type layers are connected using a metallic wire, transfer of electron can be occurred from the n-type zone to p-type zone by passing the attenuation region. After that the electron goes over the external wire of the n-type side and as a result of movement of electron an electricity flow occurs. In this process solar energy from sunlight can be altered into electricity by operating a photovoltaic system.

Electrons which are belonged in the silicon are released after striking sunlight on a photovoltaic cell and this results in the formation of holes for escaping electrons behind. For happening this, electrons from electric field move to the n-type layer and transfer holes to p-type layer. Connecting the n-type and p-type layers travel of electron can be occurred from n-type region to p-type region by passing the depletion region. Then the electron moves through the external wire of the n-type layer and thus a flow of electricity is occurred.

4. Modeling of PV Cell

The photovoltaic cell for this study is designed based on an electrical circuit. The irradiation is taken as 1000 w/m^2 as standard.

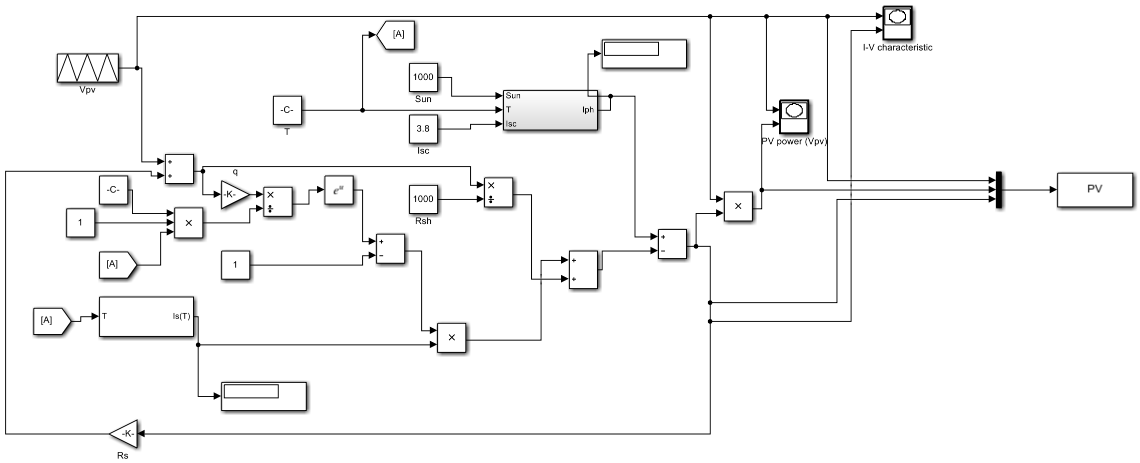

Figure 2: Schematic diagram of a photovoltaic cell.

The photocurrent can be obtained by following the diagram shown in the fig below

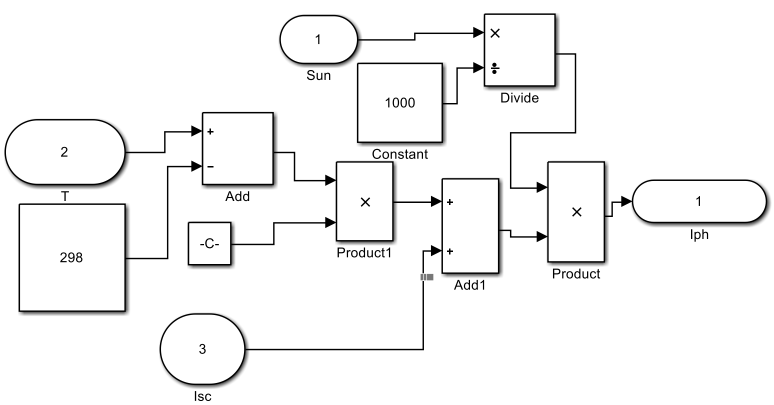

Figure 3: Schematic diagram of photocurrent with sequential steps.

From equation (1) –

$$I = I_{ph} - I_s\left(exp\frac{q(V + R_sI)}{NKT} - 1\right) - \frac{(V + R_sI)}{R_{sh}}$$

From the equation it can be known that output current from PV cell can be affected by operating temperature, series resistance, solar irradiation and shunt resistance and from the IV PV curve these effects can be understood.

5. Effect of different parameters on solar cell performance

5.1. Temperature on PV cell-

In photovoltaic system, operating temperature operates a vital role. The efficiency, the output current and the power output of a photovoltaic system changes straightly with the change of operating temperature. The performance ratio reduces with latitude as a result of increase of temperature. But in regions with higher altitude the performance ratio is higher because of lower temperature. [8]

The effect of temperature in PV cell can also be acknowledged by the equation (4) in which the reverse diode current changes with the operating temperature

$$I_s(T) = I_s\left(\frac{T}{T_{nom}}\right)^3 \exp\left[\left(\frac{T}{T_{nom}} - 1\right)\frac{E_g}{N.V_t}\right] \dots\dots\dots (4)$$

Here, T_{nom} represents the nominal temperature, E_g represents the band gap energy, V_t represents the thermal voltage. Here the reverse saturation current which can be represented in terms of temperature, is largely dependent on nominal temperature and band gap energy.

The required model or diagram to understand the impact of temperature on photovoltaic cell is shown in the fig.

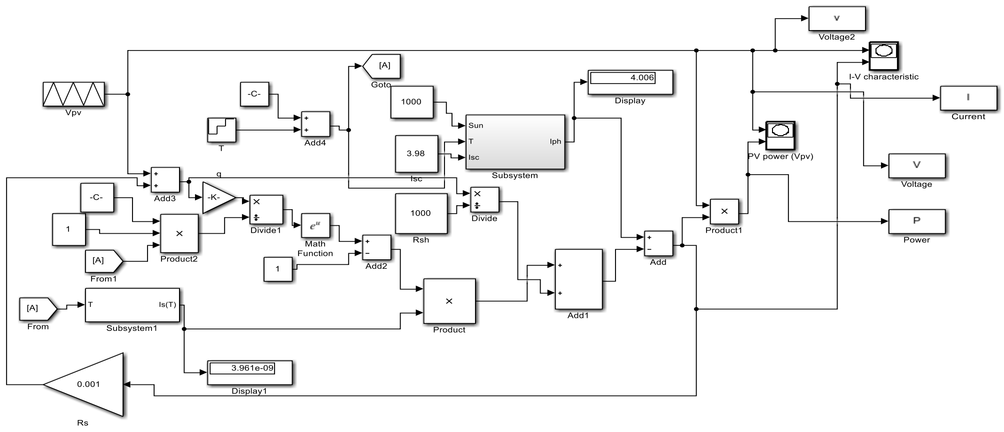

Figure 4: Schematic diagram to analyze effect of temperature on solar cell.

To understand the behavior of PV and IV curve three different temperatures are taken in this study and these are 25℃, 40℃ and 55℃ and the effect of various temperature can be shown from the fig by analyzing the IV and PV curve.

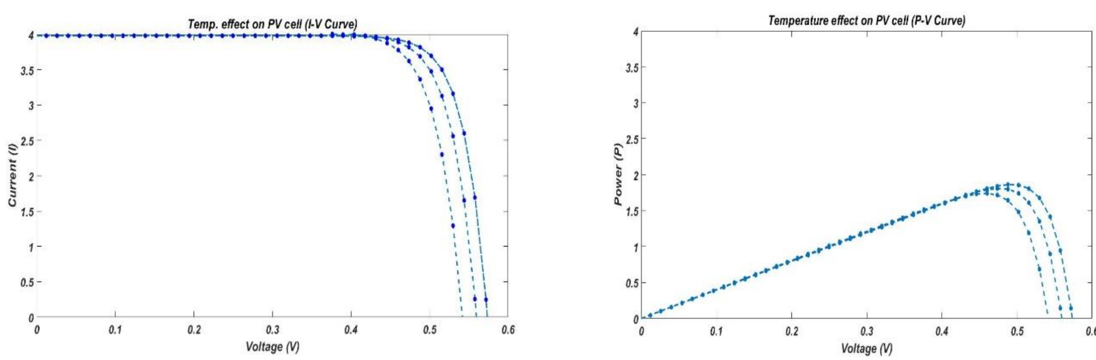

Figure 5: I-V and P-V curve to analyze the temperature effect on solar cell performance

Behavior of temperature dependent I-V characteristic curves of irradiated photovoltaic cells can be explained theoretically based on Band Theory of Solid States Physics. From fig it can be seen that the current-voltage(I-V) characteristic behavior changes with increasing temperature. The short circuit current increases and the open circuit voltage reduces with the increasing temperature. As the temperature rises, the forbidden gap reduces as well as the level of Fermi energy shifts closer to the forbidden gap's center. These processes result in a drop in the photovoltaic voltage by reducing the resistance in the PN junction [9].

5.2. Effect of Solar Irradiation on PV cell

The output power and current can be affected by the amount of solar radiation. The electrical power output rate increases with the increasing of solar irradiation rate. The thermal energy is also increased with the increasing of solar irradiation. The output electrical power as well as the thermal energy are increased by about 6.4 W and 31.3 W respectively with the increase of solar irradiation by 100 W/m^2 [10]. Concentrator can be used to get higher solar irradiation. Higher solar irradiation significantly increases the overall output of a PV system.

From equation (2)-

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

Here, K_i represents coefficient of temperature coefficient for short circuit current. From this equation it can be acknowledged that the photovoltaic current largely depends on solar irradiation.

To analyze the impact of quantity of solar irradiation on photovoltaic cell, a diagram consisting IV and PV characteristics is required which is shown in the fig. Then by running this model IV and PV characteristics curve can be gained.

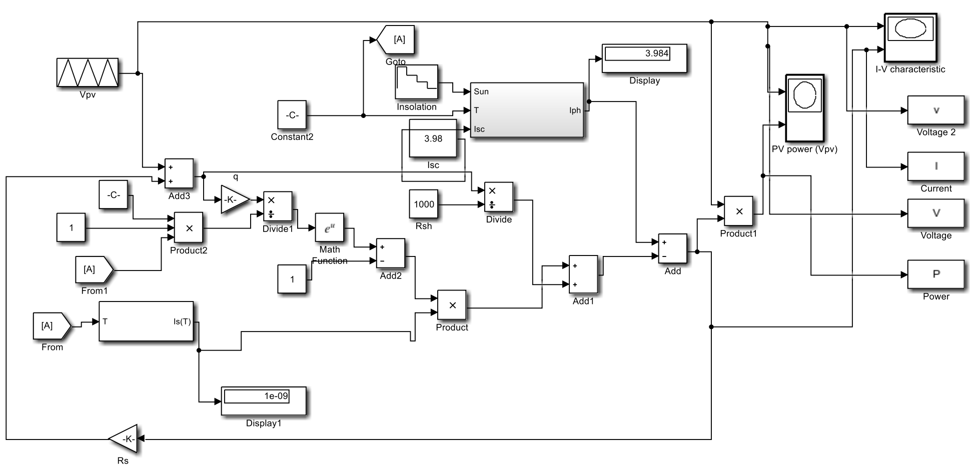

Figure 6: Schematic diagram to analyze effect of solar irradiation on solar cell.

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To analyze the effect of solar irradiation on PV cell, three different values of solar irradiation are taken in this study and the values are 1000 W/m^2, 800 W/m^2, 600 W/m^2 and 350 W/m^2. The behavior of various amounts of solar irradiation on PV cell can be understood from fig by analyzing the power-voltage and current-voltage curves.

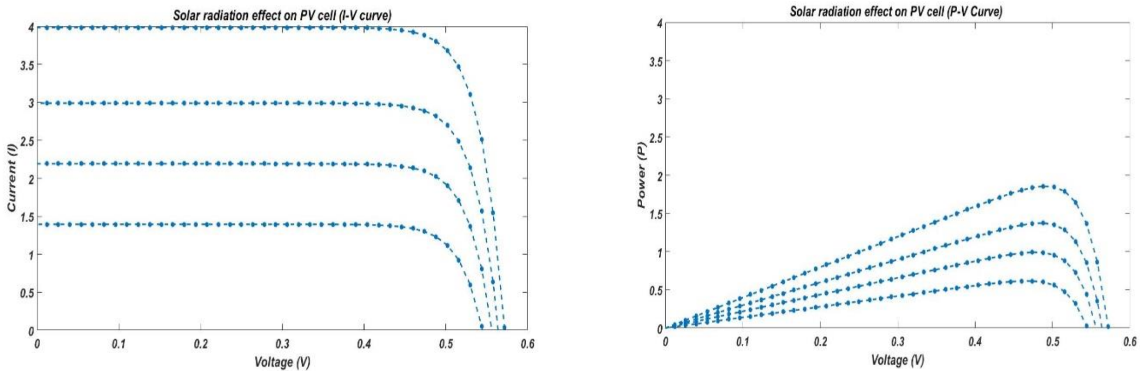

Figure 7: I-V and P-V curve to analyze the solar irradiation effect on solar cell performance

5.3. Effect of Reverse saturation current (I_s) on PV cell

The relation of cell output current with the reverse saturation current can be obtained from equation (1). The lower the reverse saturation current, the higher the output current. Enhancing of the reverse saturation current reduces the open circuit voltage.

To analyze the impact of reverse saturation current on PV cell, a diagram modeled in Simulink is shown in fig.

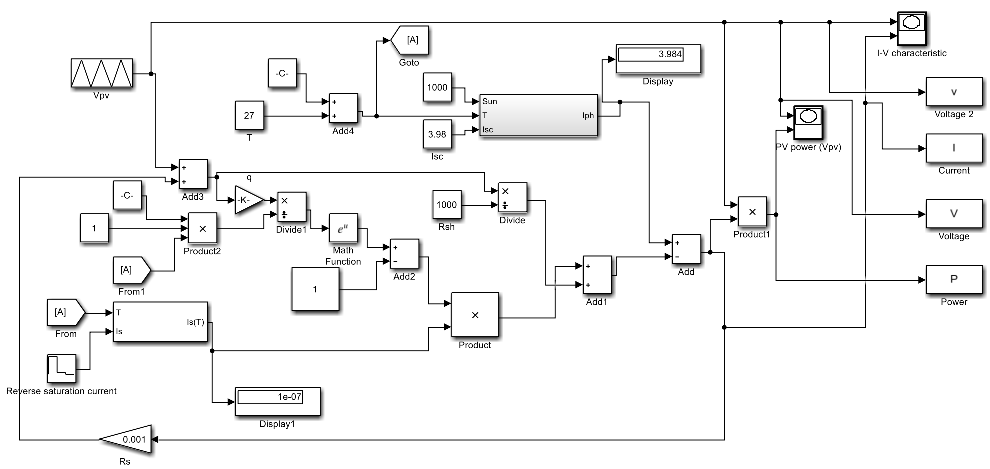

Figure 8: Schematic diagram to analyze effect of reverse saturation current on solar cell.

To check the effect of I_s on PV cell three different values of I_s are taken and analyzed. The values are taken as 1000 nm, 100 nm and 10 nm.

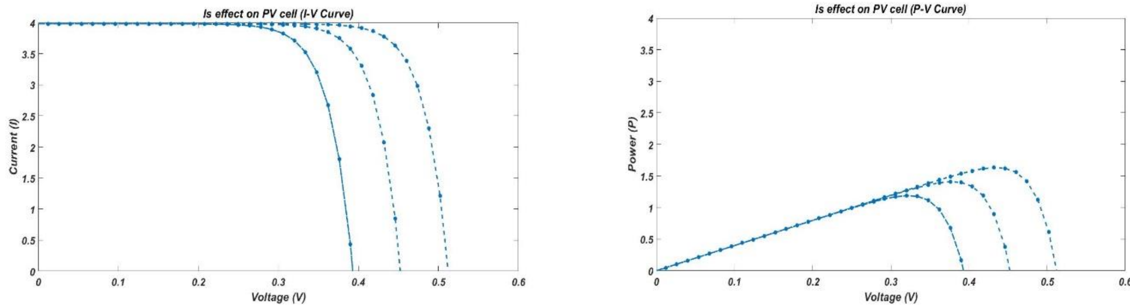

Figure 9: I-V and P-V curve to analyze the reverse saturation current effect on solar cell performance

From the IV and PV characteristic curve it can be analyzed that the output voltage and current from photovoltaic cell junction reduces by enhancing the reverse saturation current. And the output power also decreases with increasing reverse saturation current.

5.4. Effect of Series Resistance (R_s) on PV cell

From equation (1), the relation between the output current from PV cell and series resistance is obtained. It can be acknowledged from the circuit diagram (fig.1), that the series resistance has not any effect on open-circuit voltage.

To understand the effects of series resistance (R_s) a diagram is designed in Matlab/Simulink which is shown in fig.

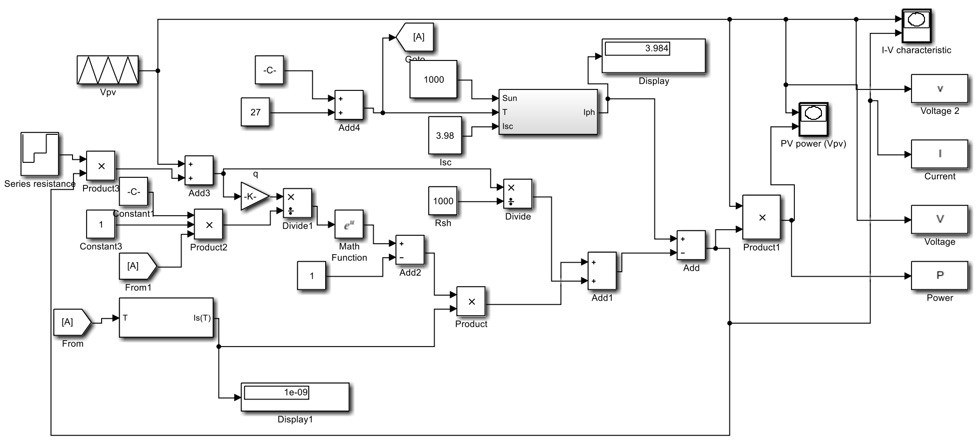

Figure 10: Schematic diagram to analyze effect of series resistance on solar cell.

At high light levels, series resistance causes a flattening of the PV output characteristic (PV and IV) and a corresponding decrease in the maximum power point voltage. The overall decline in efficiency of a PV system can be overcome by reducing the series resistance for PV system consisting optical concentrator. [11]

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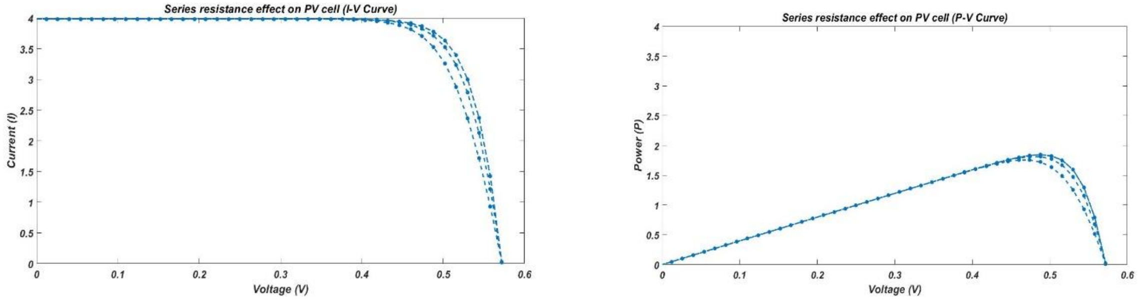

Figure 11: I-V and P-V curve to analyze the effect series resistance on solar cell performance

The simulation was run for three different values of series resistance and these are 2 mΩ, 4 mΩ and 8 mΩ. From the IV and PV characteristics curve it is clear that the power output decreases with the increase of series resistance.

5.5. Effect of Shunt Resistance on PV cell

From equation (1), the relation between output current from PV cell and shunt resistance can be obtained. The output current increases with increasing shunt resistance. From the electrical circuit diagram, it is clear to understand that there is an alternative path to pass current and in this path the shunt resistance exists. Lower shunt resistance causes increase of the current which flows through the alternative path and this reduces the output current from the photovoltaic cell junction as well as the voltage from photovoltaic cell junction also reduces.

Fig () shows the diagram that is required to understand the impact of shunt resistance by simulating IV and PV characteristic curves.

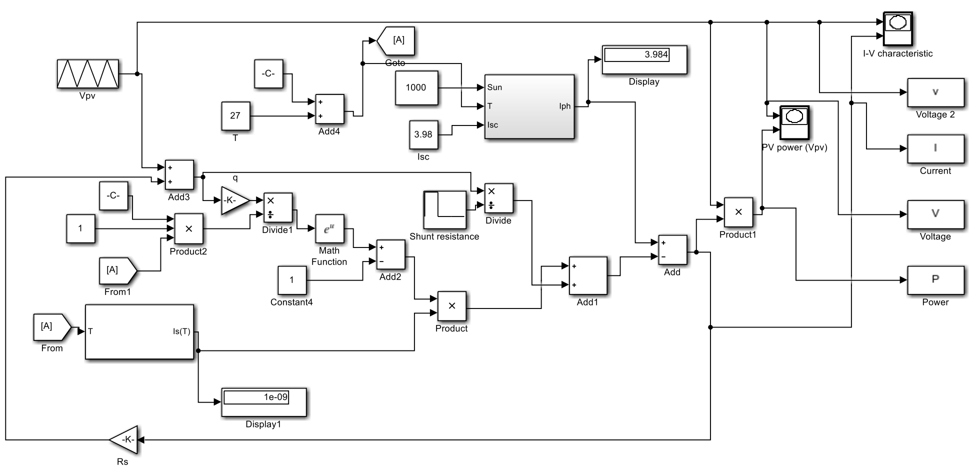

Figure 12: Schematic diagram to analyze effect of shunt resistance on solar cell.

To understand the effect of shunt resistance (R_{sh}) on PV cell three different values of shunt resistance were taken such 1000 Ω, 10 Ω and 1 Ω. The leakage current increases with the decrease of shunt resistance.

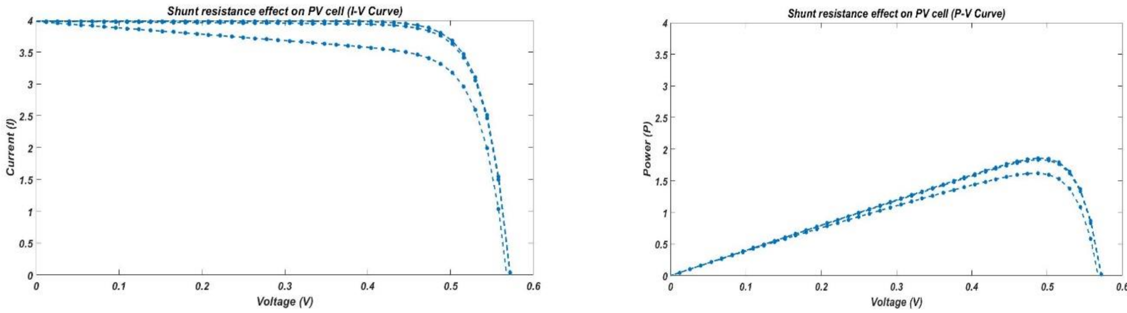

Figure 13: I-V and P-V curve to analyze the effect shunt resistance on solar cell performance

From the P-V and I-V curves it can be understood that with the increasing of shunt resistance the maximum power is also increased. From the IV curve it can also be seen that the amount of output voltage increases with the increase of shunt resistance.[12][13]

6. Modeling of PV module

The blocks which were used to model the complete PV module were developed in matlab / Simulink software. First two blocks in the PV module (Fig) are two subsystems and in the first subsystem the values are were taken as follows-

Operating Temperature	25°C
Solar Irradiation	1000 W/m^2
Series resistance vector output	0.008
Shunt resistance	1000 Ω

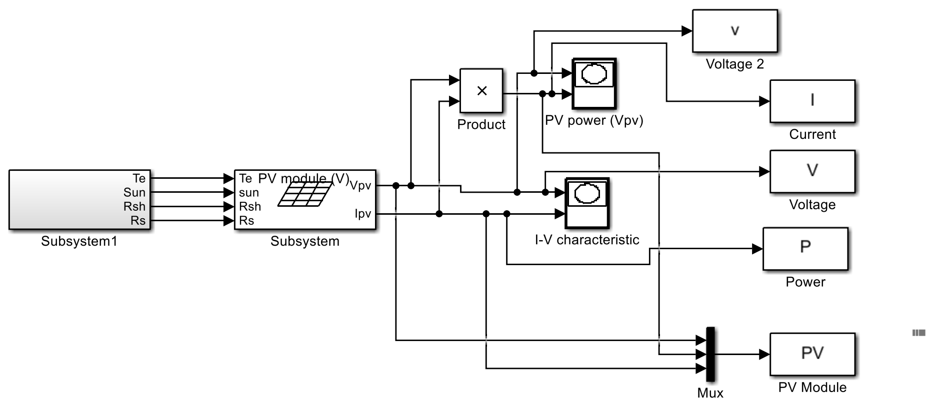

Figure 14: Schematic diagram of the designed PV module

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6.1. Tracking the maximum power point for the designed module from characteristic curve:

The PV module system is modeled using matlab software and the simulating the model characteristic curve is gained. From the characteristic curve maximum power point can be achieved.

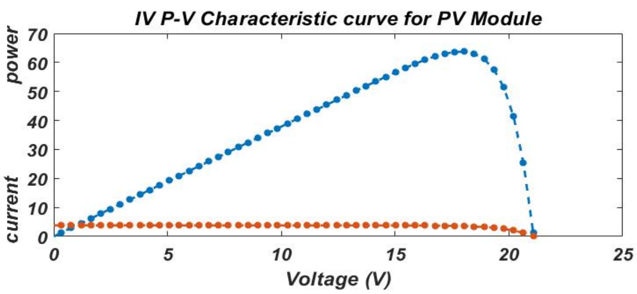

Figure 15: Graph to track maximum power point for the PV module.

The red line of this graph shows the current-voltage curve and the blue curve shows the power-voltage curve and by analyzing the graph, the maximum point can be obtained and from that point the amount of highest output power can be obtained. And from the graph the maximum power is achieved as 62 Watt.

7. Model of PV Panel

PV panel forms by connecting PV cells. In this study the PV panel consists of 60 PV cells and the model which is selected for simulation is MX Solar USA MX60-245.

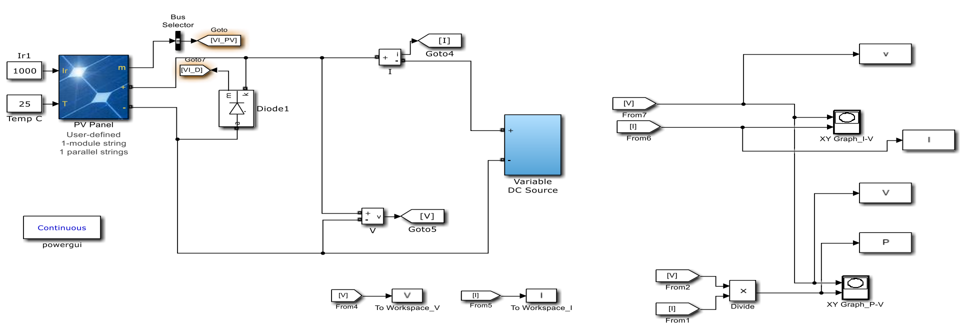

Figure 16: Schematic diagram of PV panel

Table 1: The operating parameters of MX Solar USA MX60-245 is given below in the table.

Maximum output Power (W)	244.915
Open Circuit Voltage V_{OC} (V)	38.3
Maximum voltage V_{mp} (V)	30.5
Short circuit current I_{SC} (A)	8.62
Maximum Current I_{mp} (A)	8.03
Light Generated current I_L (A)	8.6331
Temperature coefficient of open circuit Voltage (V_{OC}) (%/°C)	-0.34799
Shunt Resistance R_{sh} (Ω)	184.1492
Temperature coefficient of short circuit current (I_{SC}) (%/°C)	0.103

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Saturation current of diode I_0 (A)	2.0318e-10
Cells per module	60
Series Resistance R_s (Ω)	0.27934
Ideality factor of diode	0.27934

8. Model of PV Array

The array is modeled in MATLAB/Simulink software inserting PV modules and inverter and all the blocks are designed using MTALAB software. There are six PV modules in the array and these modules had same characteristics and properties. The PV modules are connected with an inverter. The inverter converts the output direct current (DC) into alternative current (AC). The series connected solar cells form an PV module and the interconnection of series and parallelly connected PV cells form an array. The performance of an PV array can be rated by the output DC power from a PV system.

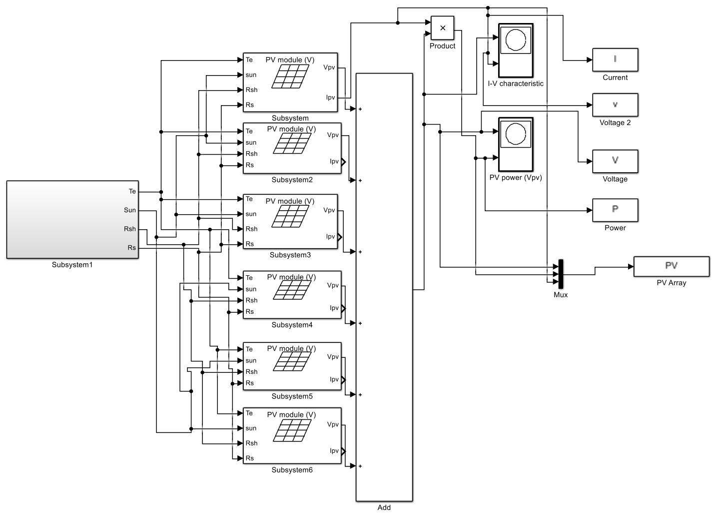

Figure 17: Schematic model of PV array consisting 6 PV modules.

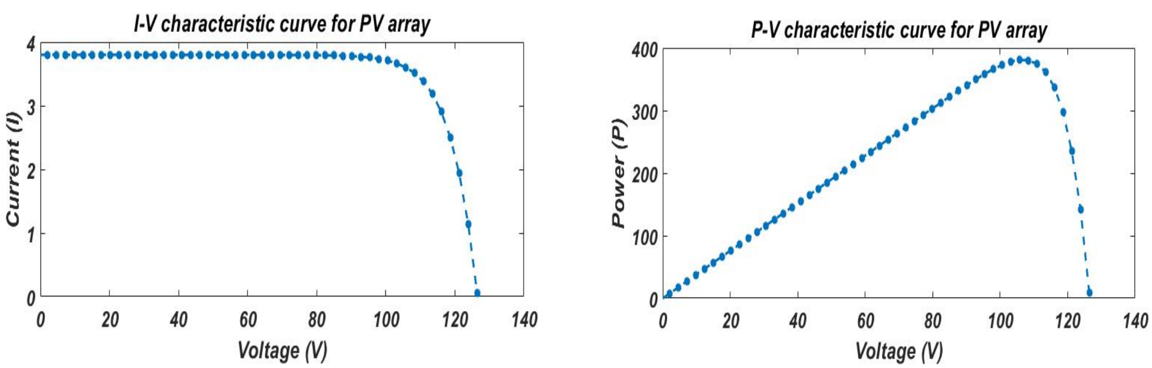

Figure 18: The PV and IV characteristics curve for the PV array

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From the power-voltage graph the maximum power point can be obtained. Characteristics of the photovoltaic array can be analyzed by the characteristic curve. Maximum output voltage and maximum output current can be tracked from these characteristic curves.

9. Tracking the Maximum Power point for MX Solar USA MX60-245 from characteristic curve

The maximum power point represents the point where the maximum output power is achieved. In this paper, to get gain the maximum power point (MPP) three points were taken for three different temperatures with the same value of solar irradiation (1000 W/m^2).

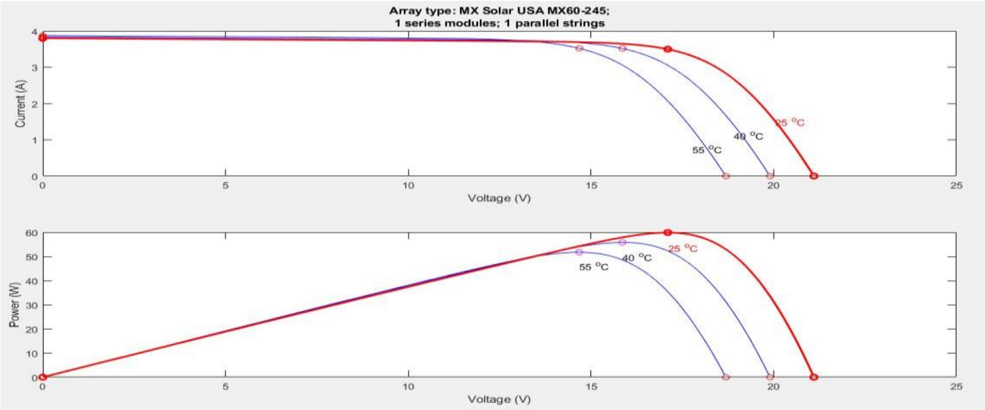

Figure 19: Maximum Power point for MX Solar USA MX60-245

From the characteristic curve three points are shown for three different temperature 25℃, 40℃ and 55℃. The upper point belongs for 25℃ operating temperature and 1000 W/m^2 where the output power is 60 Watt. The intermediate point exists for 40℃ operating temperature and 1000 W/m^2 where the power output is 55 Watt. The lowest point compared to other points belongs for 55℃ and same amount of solar radiation where 50 watt is the output power. From the characteristic curve the maximum power point has been found for 25℃ and 1000 W/m^2.

10. Conclusion

In this study, a photovoltaic panel is modeled using Matlab / Simulink software applying different blocks and the model base stands on a mathematical model. The power-voltage and current-voltage characteristic curves are gained by simulating the developed photovoltaic model. From the characteristic curves maximum power point is tracked in this study. Effects of different parameters on photovoltaic cell such operating temperature, solar irradiation, reverse saturation current, series resistance, shunt resistance are analyzed in this study. In this study, three different values of temperature (25℃, 40℃ and 55℃) and one specified value of solar irradiation (1000 W/m^2) are taken to understand the characteristic curve and to achieve the highest power point. After analyzing the characteristic curve, the maximum output power is obtained at the upper point that belongs for 25℃ operating temperature and 1000 W/m^2 solar irradiation. The maximum power is also compared in this paper and it is analyzed that amount of output power in the designed model and the selected model

(MX Solar USA MX60-245) are very near. For the designed P-V module the output power is 62 watt and this amount is 60 watts for MX Solar USA MX60-245.

References:

[1] R. J. Brecha, "Emission scenarios in the face of fossil-fuel peaking," *Energy Policy*, vol. 36, no. 9, pp. 3492–3504, Sep. 2008, doi: 10.1016/J.ENPOL.2008.05.023.

[2] J. M. Dyrstad, A. Skonhoft, M. Q. Christensen, and E. T. Ødegaard, "Does economic growth eat up environmental improvements? Electricity production and fossil fuel emission in OECD countries 1980–2014," *Energy Policy*, vol. 125, pp. 103–109, Feb. 2019, doi: 10.1016/J.ENPOL.2018.10.051.

[3] Q. Wang and H. N. Qiu, "Situation and outlook of solar energy utilization in Tibet, China," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 2181–2186, Oct. 2009, doi: 10.1016/J.RSER.2009.03.011.

[4] N. A. Zainal, Ajisman, and A. R. Yusoff, "Modelling of Photovoltaic Module Using Matlab Simulink," *IOP Conference Series: Materials Science and Engineering*, vol. 114, no. 1, Mar. 2016, doi: 10.1088/1757-899X/114/1/012137.

[5] E. Dursun and O. Kilic, "Comparative evaluation of different power management strategies of a stand-alone PV/Wind/PEMFC hybrid power system," *International Journal of Electrical Power & Energy Systems*, vol. 34, no. 1, pp. 81–89, Jan. 2012, doi: 10.1016/J.IJEPES.2011.08.025.

[6] H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE Transactions on Energy Conversion*, vol. 23, no. 1, pp. 302–310, Mar. 2008, doi: 10.1109/TEC.2007.914308.

[7] S. Sheik Mohammed-A, "Modeling and Simulation of Photovoltaic module using MATLAB/Simulink," *International Journal of Chemical and Environmental Engineering*, vol. 2, no. 5, 2011.

[8] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review," *Energy Procedia*, vol. 33, pp. 311–321, Jan. 2013, doi: 10.1016/J.EGYPRO.2013.05.072.

[9] M. Libra, V. Poulek, and P. Kouřím, "Temperature changes of I-V characteristics of photovoltaic cells as a consequence of the Fermi energy level shift," vol. 63, no. 1, pp. 10–15, doi: 10.17221/38/2015-RAE.

[10] R. Nasrin, M. Hasanuzzaman, and N. A. Rahim, "Effect of high irradiation on photovoltaic power and energy," *International Journal of Energy Research*, vol. 42, no. 3, pp. 1115–1131, Mar. 2018, doi: 10.1002/ER.3907.

[11] M. Wolf and H. Rauschenbacht, "SERIES RESISTANCE EFFECTS ON SOLAR CELL MEASUREMENTS *," *Advanced Energy Conversion*, vol. 3, pp. 455–479, 1963.

[12] I. Lombardero and C. Algora, "Impact of shunt resistance on the assessment of multijunction I-V," p. 60001, 2012, doi: 10.1063/1.5053525.

[13] A. D. Dhass, E. Natarajan, and L. Ponnusamy, "Influence of shunt resistance on the performance of solar photovoltaic cell," *Proceedings - ICETEEEM 2012, International Conference on Emerging Trends in Electrical Engineering and Energy Management*, pp. 382–386, 2012, doi: 10.1109/ICETEEEM.2012.6494522.