

Modelling and Analysis of Single Diode Photovoltaic Module using MATLAB/Simulink

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ABSTRACT

The growing concern over environmental degradation resulting from combustion of fossil fuels and depleting fossil fuel reserves has raised awareness about alternative energy options. Renewable energy system is perfect solution of this problem. This paper presents a mathematical model of single diode solar photovoltaic (SPV) module. SPV cell generates electricity when exposed to sunlight but this generation depends on whether condition like temperature and irradiance, for better accuracy all the parameters are considered including shunt, series resistance and simulated in MATLAB/Simulink. The output is analyzed by varying the temperature and irradiance and effect of change in shunt and series resistance is also observed.

Keywords:- Solar photovoltaic (SPV), standard test condition (STC), mathematical model.

I. INTRODUCTION

Photovoltaic cell is the building block of the SPV system, and semiconductor material such as silicon and germanium are the building block of SPV cell. When a SPV module is exposed to sunlight it produces electric power if connected to a suitable load. Basically solar cell is a PN junction and when sunlight (photon) is allowed to fall on the surface of a solar cell, the electrons get sufficient energy and jump to the conduction band of the semiconductor from the valence band and become free to move [1]. When a semiconductor (silicon) atom absorbs enough energy from sunlight, it will release an electron. This electron will urgently seek a free place to land. It can be useful to think of the electron as frenetically, electrically, seeking a new home. Electrons are released more easily if the molecules are unstable. This is why impure, or "doped," silicon is used in the production of photovoltaic cells [2].

A potential difference is created due to the rearrangement of electrons across the terminals. With the breaking of covalent bond inside the atom of semiconductor, electron and hole pairs are generated resulting in the formation of electric field.

Solar Photovoltaic system is highly reliable as it has an average life of more than 20 years because the conversion of sunlight into electricity is a silent and instantaneous process and there are no mechanical parts to wear out. But its efficiency decreases with the ageing of the components. SPV system has almost no harmful effect on our environmental condition. The characteristic of a solar cell varies with some weather conditions like

clouding, partial shading and intensity of radiation i.e. it would be highly beneficial to improve the efficiency of a SPV module so that more and more energy can be extracted. PV cell characteristics are described by the current and voltage levels. If there is no load connected across the SPV cell then no current will flow and the voltage developed across the SPV cell is called open circuit voltage (V_{oc}) and if its two terminals are directly connected then the maximum current flows called short circuit current (I_{sc}).

A SPV cell generates approximate voltage around 0.6 volts. To increase the voltage and current output capacity, solar cells are connected in series and parallel simultaneously or it can be connected in both series and parallel [1,3].

Various types of tested and improved SPV technologies exist based on standard microelectronic manufacturing processes. Where the crystalline (SPV module light-to-electricity efficiency: $\eta = 10\% - 15\%$) and multi-crystalline ($\eta = 9\% - 12\%$) silicon cells. Other types are: thin-film cadmium telluride ($\eta = 9\%$), thin-film amorphous silicon ($\eta = 10\%$), and thin-film copper indium diselenide ($\eta = 12\%$) [2]. Performance of SPV devices at standard test condition (STC) are specified by datasheets.

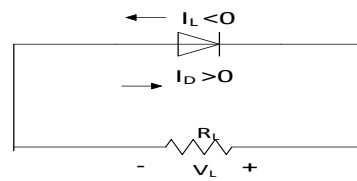
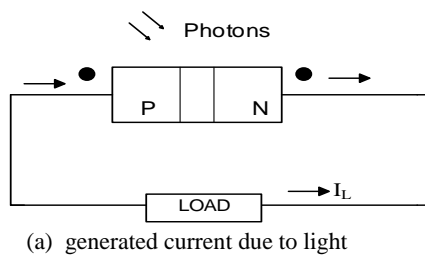
Various modelling technique of SPV cell is proposed till now but two most adapted techniques are single diode model and two diode model. Two diode models is a complex way of designing SPV cell, has higher accuracy as the effect of recombination of carriers can be represented by other diode. But this accuracy comes at a cost of higher complexity and more computational time is required as the number of unknown parameters is

more than in single diode model [4]. Single diode model is proposed in this paper for accuracy as well as simplicity. It requires three parameters short circuit current, open circuit voltage and ideality factor to completely characterize the IV curve. Model with series and shunt resistance is accurate and practical, easier to analyze and extract the unknown parameters.

II. WORKING OF SOLAR CELL

A silicon PV cell is composed of a thin wafer consisting of an ultra-thin layer of phosphorus-doped (N-type) silicon on top of a thicker layer of boron-doped (P-type) silicon. Sunlight consists of packets of solar energy called photons. When PV cell is exposed to these photons, many of the photons are reflected, pass right through, or get absorbed by the solar cell. When sufficient number of photons gets absorbed by the negative layer of the solar photovoltaic cell, electrons get freed from the negative semiconductor (silicon) material [3]. Based on the manufacturing process of the positive layer, these free electrons naturally migrate to the positive layer creating a voltage differential, similar to a household battery. As a result an electric current start flowing from the positive layer of semiconductor to the negative layer called light generated current (I_L) shown in Fig. 1.

Photovoltaic cell efficiency is determined under standard test conditions (STC) unless stated in other way. STC specifies irradiance (G) of 1000 W/m² and a temperature of 25°C with an air mass spectrum 1.5 (AM1.5) while the cell quality is determined by fill factor. Fill factor [5,10] of a solar cell is defined as the ratio of maximum power that can be obtained to the product of short circuit current and open circuit voltage. Commercial solar cells have a fill factor > 0.7 and grade B cells have fill factor usually between 0.4 and 0.7 [10]. Photovoltaic cell with a higher fill factor has a lower equivalent series resistance and a higher equivalent shunt resistance, so the internal losses due to dissipation of current produced would be less.



(b) dark current generation principle
 Fig. 1. Working principle of solar cell.

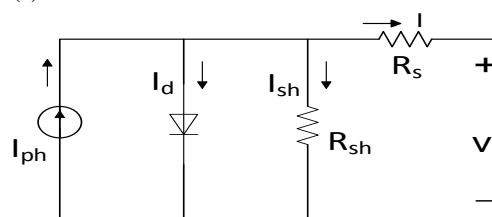
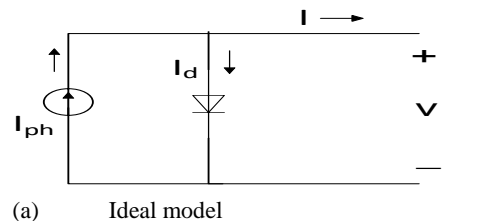
When the diode is forward biased and no sunlight is incident on it then free electrons from n-side goes to p-side leaving a hole in n-side. Then in p-side this electron recombines with a hole, and ejecting one electron from p-side through the wire. So the current flows from the p-side to n-side through the depletion region, which is opposite to the light generating current known as dark current.

III. SIMULATION AND MODELLING OF A PV CELL

3.1 Modelling of single diode SPV cell

Equivalent circuit of a single diode model has a current source (photocurrent), a diode parallel to it in opposite direction shown in Fig. 2(a). But in a practical model resistors are considered in shunt and series as shown in the Fig. 2(b) [6]. For ideal case series resistance should be zero and shunt resistance should be infinity but practically they have some significant values.

The cell current for the ideal model is given by $I = I_{ph} - I_d$.



(b) Practical model with Rsh and Rs
 Fig. 2. Single diode PV cell model

Where I_{ph} is photocurrent, I_d is the diode current, I_{sh} is current through shunt resistance, I is the output current, R_{sh} is the shunt resistance, R_s is series resistance and V is the cell voltage. Variation in the shunt resistance R_{sh} does not affect the efficiency of the cell but efficiency of a SPV cell greatly depends on the variation in series resistance R_s [11,12]. As R_{sh} of the cell is inversely proportional to the shunt

leakage current to ground so it can be assumed to be very large value for a very small leakage current to ground.

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

$$\text{Where, } I_d = I_{rs} \left[\exp \left(\frac{V_d}{A n_s V_t} \right) - 1 \right] \quad (2)$$

n_s is number of PV cells in series, I_{rs} and V_d is diode reverse saturation current and diode voltage, 'A' is diode ideality factor in equation 2, V_d is calculated by applying Kirchoff's voltage law ($V_d = V + IR$), V_t is the diode thermal voltage and given as $V_t = kT_{op}/q$. k is the boltzmann's constant (1.381×10^{-23} J/K), T_{op} is the actual temperature (in Kelvin), q is charge of an electron (1.67×10^{-19} coulomb) [5].

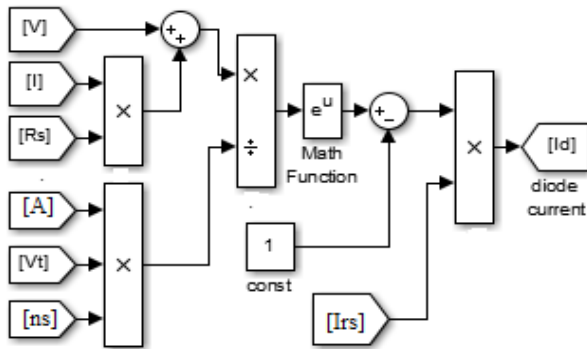


Fig. 3. Modelling in Simulink for diode current.

A two diode model has better accuracy because due to an extra diode the effect of recombination of carriers can be represented. But due to complexity in modelling of two diode model in this paper the single diode is proposed for both simplicity and accuracy. Generally on the data sheet the parameter like photocurrent, series resistance, shunt resistance, diode ideality factor and band gap energy of the semiconductor material are not provided [2,9]. Using proper mathematical equations, better accuracy can be achieved by calculating the different unknown values with the help of known values provided by manufacturer.

3.2 Determination of photocurrent

When PV cell is short circuited, $I_{ph,sc} = I_{sc,sc}$

$I_{sc,sc}$ = short circuit current at STC

$I_{ph,sc}$ = photovoltaic current at STC

The photo current (I_{ph}) depends on irradiance (G) in (W/m^2) and temperature in kelvin (K) [6].

$$I_{ph} = \frac{G}{G_{stc}} \left[I_{ph,sc} + \beta (T_{op} - T_{stc}) \right] \quad (3)$$

Photocurrent is given as per equation 3. Values of the parameters mentioned in the right hand side of given equation is used and simulated in simulink as

shown in fig 4. G_{stc} and T_{stc} is the value of irradiance and temperature at STC, β is the short circuit current and the values are rendered by the manufacturer.

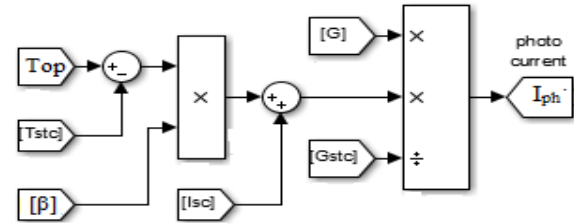


Fig. 4. Modelling in Simulink for photovoltaic current.

3.3 Determination of diode saturation current

Diode saturation current I_{rs} is required to determine I_d as per equation. It is a function of band gap energy of material, temperature and is given by

$$I_{rs} = D T_{op}^3 \exp \left(\frac{-q E_g}{A k T_{op}} \right) \quad (4)$$

At standard test condition the above equation is given by:

$$I_{rs,sc} = D T_{stc}^3 \exp \left(\frac{-q E_g}{A k T_{stc}} \right) \quad (5)$$

Where E_g is band gap energy and D is diffusion factor [8].

By solving equation (4) and (5) we get

$$I_{rs} = I_{rs,sc} \left(\frac{T_{op}}{T_{stc}} \right)^3 \exp \left[\frac{q E_g}{A k} \left(\frac{1}{T_{stc}} - \frac{1}{T_{op}} \right) \right] \quad (6)$$

Equation (6) is described in Fig. 5 with the help of MATLAB /Simulink as shown.

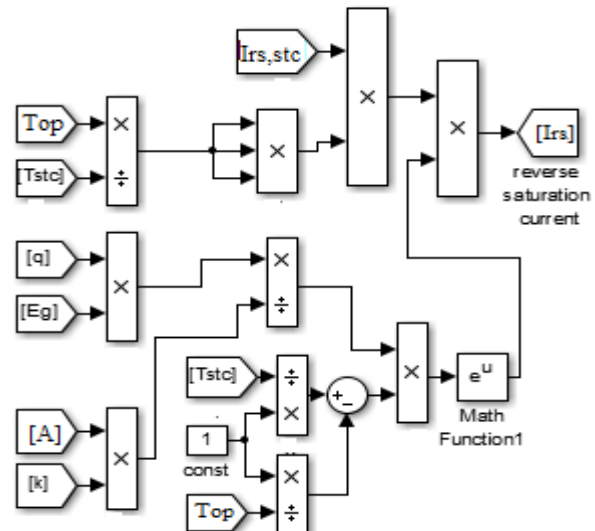


Fig. 5. Modelling in Simulink for reverse saturation current.

3.4 Determination of diode saturation current at STC

At STC for open circuit condition the cell output current becomes zero and equation (1) can be written as

$$0 = I_{ph,STC} - I_{rs,STC} \left[\exp \left(\frac{V_{oc}}{A n_s V_t} \right) - 1 \right] \quad (7)$$

As the cell current (I) and current through shunt resistance (I_{sh}) becomes zero for open circuit and the diode voltage (V_d) will become the open circuit voltage (V_{oc}) and $I_{0,STC}$ will be

$$I_{rs,STC} = \frac{I_{ph,STC}}{\exp(V_{oc}/A n_s V_t) - 1} \quad (8)$$

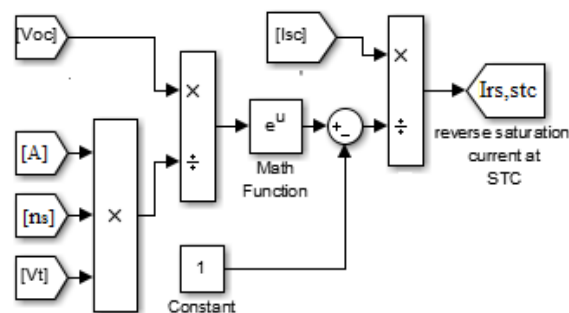


Fig. 6. Modelling in Simulink for saturation current at STC.

3.5 Determination of current through shunt resistance

Voltage across R_{sh} can be written as $(V+IR_s)$ by applying kirchoff rule in Fig 2(b). so the current flowing through the shunt resistance can be given as:

$$I_{sh} = \frac{V + IR_s}{R_{sh}} \quad (9)$$

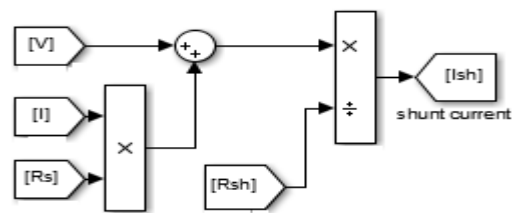


Fig. 7. Modelling in Simulink for shunt resistance current.

The solar photovoltaic model used in this simulation has 72 cells in series. So the open circuit voltage will be 43.2 volt but short circuit current remains 3.2 Amp. To get higher output current the cells are connected in parallel and the current increases linearly with the number of parallel cells connected.

3.6 Determination of output voltage and current

To calculate the output voltage a variable load is connected across the two terminals of SPV module as shown in the Fig. 8 and it is observed that

with the increment in load the voltage is also increasing [8]. To calculate the output current, I_{ph} , I_d and I_{sh} is calculated and put in the equation 1. Voltage and current obtained from this simulation model is again used as input for calculating I_d and I_{sh} and the process continues as a loop.

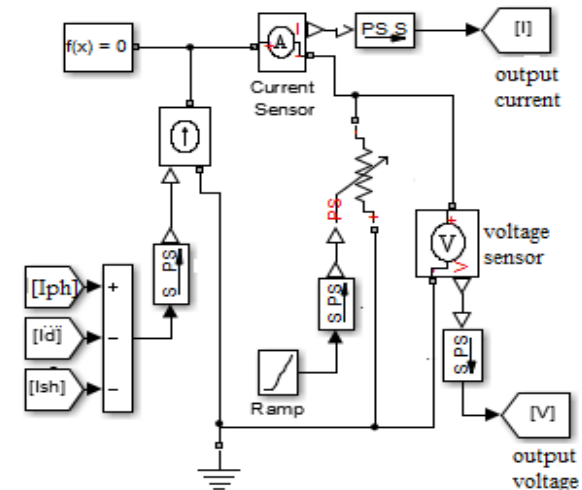


Fig. 8. Modelling in Simulink for cell current and voltage.

IV. SIMULATION RESULTS AND DISCUSSION

4.1 Effect of varying irradiance

When irradiance is varying there is a very small change in voltage, but there a substantial change is observed in current with varying irradiance. When irradiance is decreasing current is decreasing proportionally as shown in Fig. 9.

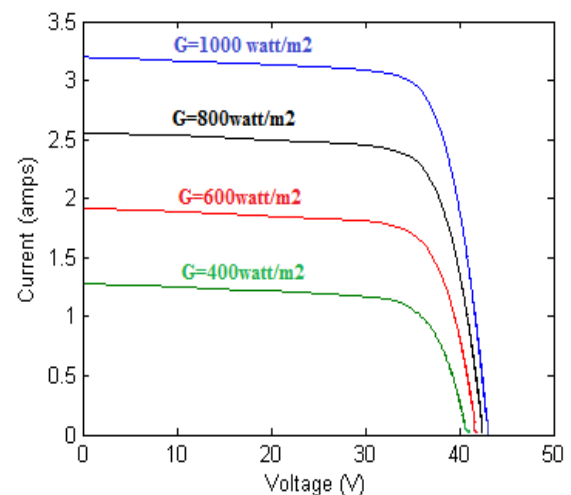


Fig.9. I-V curve plot for varying irradiance.

As it is observed in Fig. 9 that as the irradiance is decreasing current is also decreasing but change in voltage is subtle. So the change in current is dominating the change in power as power of a SPV cell is given as $V \cdot I \cdot \text{fill factor}$. PV curve is simulated and the result is shown in Fig. 10.

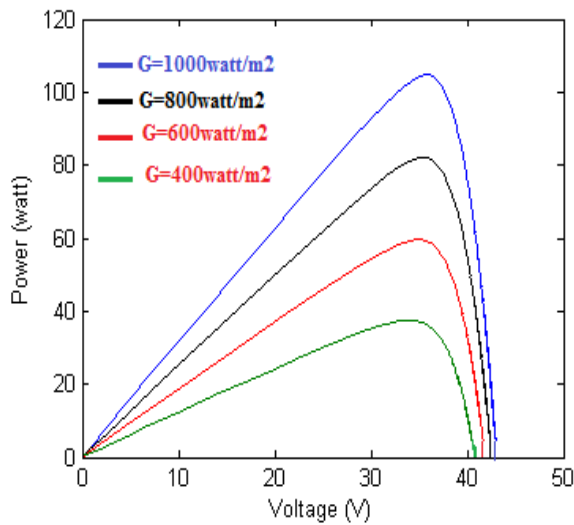


Fig. 10. P-V curve plot for varying irradiance.

4.2 Effect of varying temperature

Temperature of the vicinity of SPV cell is never constant and its effect is observed in the output current and voltage of SPV cell. With the variation in temperature the output current does not vary but the voltages do. As the temperature increase, output voltage decreases and vice versa as shown in Fig. 11.

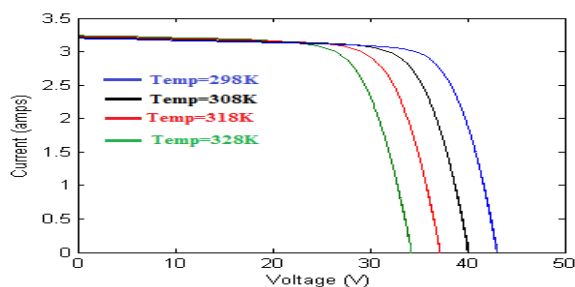


Fig. 11. I-V characteristics with varying temperature.

As it is observed that with increasing temperature, current is not changing but voltage is decreasing and so the power also, the effect is shown in Fig. 12.

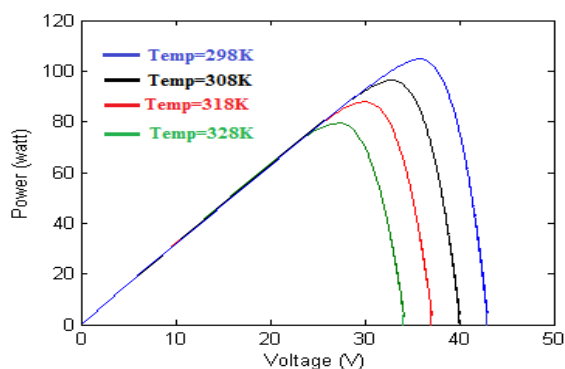


Fig. 12. P-V characteristic with varying temperature.

4.3 Effect of series resistance

Series resistance R_s is present in SPV cell results in reduced fill factor. In ideal situation it should be zero. It does not affect the open circuit voltage of solar cell but if the resistance is very high then it results in the reduction of short circuit current. IV characteristic with varying series resistance is shown in Fig. 13.

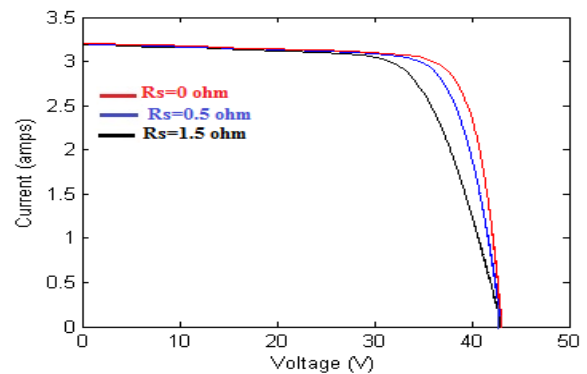


Fig. 13. I-V characteristic with varying series resistance R_s .

With the variation in series resistance we can see that maximum power point (MPP) is varying in the Fig. 14.

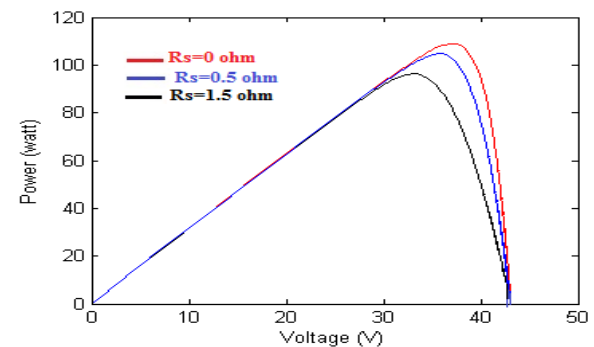


Fig. 14. P-V characteristic with varying series resistance (R_s).

4.4 Effect of shunt resistance

R_{sh} is present typically due to manufacturing defect. In ideal situation it should be infinite. Shunt resistance R_{sh} provide an alternative path to the generated photo current, as a result the output voltage decreases and the efficiency decreases. The effect of a shunt resistance is severe in lower irradiance as the generated photocurrent is already low and loss in shunt resistance is higher, so the impact is larger. IV curve with varying R_{sh} is shown in Fig. 15.

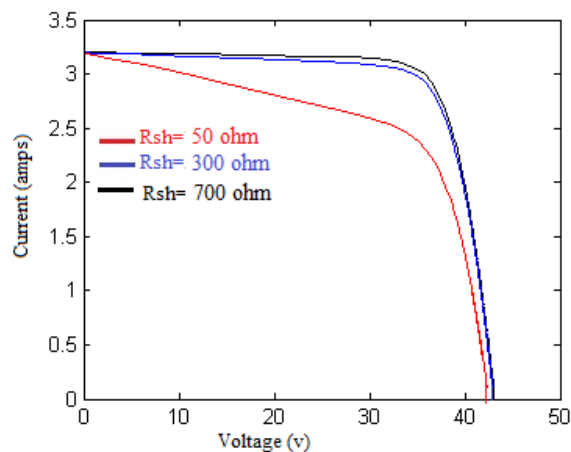


Fig. 15. I-V characteristic with varying shunt resistance (R_{sh}).

As the shunt resistance is increasing PV curve is shifting upward and output power is increasing. Simulation result is shown in Fig. 16.

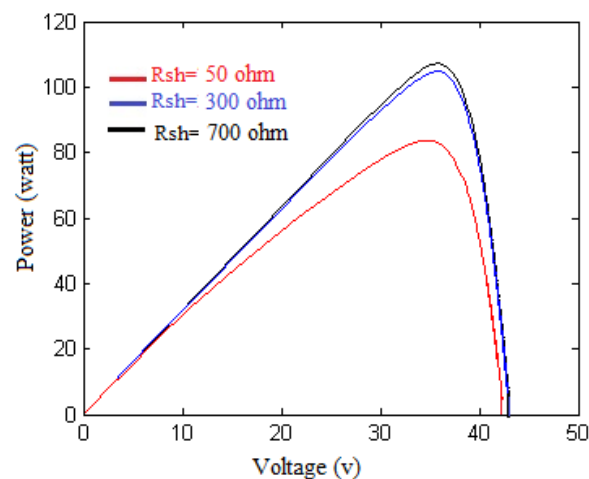


Fig. 16 .P-V characteristic with varying shunt resistance (R_{sh}).

IV. CONCLUSION

In this paper the mathematical modelling was described by considering all the parameters of solar cell. Output characteristic of solar cell are simulated in MATLAB/Simulink by considering all the equations with appropriate values of parameters. It is concluded that the series and shunt resistance should have the value for which the performance of the cell is better. The series resistance should be less and shunt resistance should be high. The main source of the solar cell is temperature and irradiance. The variation due to these two parameters are shown and discussed in this paper. The cell output is good with low temperature and more irradiance.

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