



Matlab / simulink based study of photovoltaic cells / modules / array and their experimental verification

Savita Nema, R.K.Nema, Gayatri Agnihotri

Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal, India

Abstract

A Matlab-Simulink based simulation study of PV cell/PV module/PV array is carried out and presented in this paper. The simulation model makes use of basic circuit equations of PV solar cell based on its behaviour as diode and comprehensive behavioural study is performed under varying conditions of solar insolation, temperature, varying diode model parameters, series and shunt resistance etc. The study is helpful in outlining the principle and intricacies of PV cell/modules and may be used to verify the impact of different topologies and control techniques on the performance of different types of PV systems. The PV module/Array performance is immensely marred by shading effect and its P-V characteristics exhibit multiple maxima. The Matlab/simulink based study therefore also points out significance of locating maximum power point for a given Module/Array. An experimental verification is also carried out in the lab by developing a PC based data acquisition system, which is also briefly discussed.

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Keywords: Matlab/Simulink, PV model parameters, Insolation, PV cell/module/array.

1. Introduction

The field of Photovoltaic (PV) has experienced a remarkable growth for past two decades in its widespread use from standalone to utility interactive PV systems [1, 2]. Solar cells are devices that convert photons into electric potential in a PN silicon junction (or other material). A PV cell is a basic unit that generates voltage in the range of 0.5 to 0.8 volts depending on cell technology being used. This small generation is not of much commercial use if these cells are not integrated and connected together in the module to give the handsome voltage at least to charge a standard battery of 12 volts. Thus what we see physically in a PV system is the commercially available module; which are further connected in series and parallel to form a PV Array as per the system requirement of voltage and the current. A typical PV module is made up of around 36 or 72 Cells connected in series, encapsulated in a structure made of Aluminum and Tedlar [3], depending on the application and type of cell technology being used. Among prominent Cell technology Monocrystalline, Polycrystalline and thin Film technologies e.g amorphous silicon (a-Si), copper indium diselenide (CuInSe₂) and cadmium telluride (CdTe) are commercially available. The monocrystalline and polycrystalline are based on costly microelectronic manufacturing process and their sunlight to electrical efficiency varies from 10%-15% for monocrystalline and 9%-12% for polycrystalline cells. Among Film Cell technology, a-Si has $\eta=10\%$, CuInSe₂ has $\eta=12\%$, and CdTe has $\eta=9\%$ [4]. Other novel technologies such as thin layer silicon and dye-sensitized nano-structured materials are in early development stage and have $\eta=9\%$.

The monocrystalline PV Cell/module has best efficiency among all commercially available technology and therefore is a focus of present study. The present paper carries out simulation based study of the Photovoltaic cell; a fundamental unit of generation, and PV modules; a commercially available unit for monocrystalline technology. The genesis of PV cell has evolved through simultaneous development in semiconductor material and processing technology as the PV cell largely behaves like a PN junction (diode) which has been put under illumination for electricity generation. A PV cell model as described in sections to follow therefore has diode as paradigm element and the characteristics difference in cell's electrical behaviour is brought in by materials constant and is normally modelled by two important diode model parameters e.g. N & I_s . The monocrystalline technology presently under study is best modelled using one diode equivalent circuit whereas the other competitive technology of same class i.e. polycrystalline is modelled using two diode equivalent circuit.

2. PV cell model

A mathematical description of current - voltage terminal characteristics for PV cells is available in literature. The single exponential equation (1) which models a PV cell is derived from the physics of the PN junction and is generally accepted as reflecting the characteristic behavior of the cell. A double exponential equation may be used for the polycrystalline silicon cells [5].

$$I = I_{ph} - I_s \left(\exp \frac{q(V + IR_s)}{N.K.T} - 1 \right) - \frac{(V + IR_s)}{R_{sh}} \quad (1)$$

where

I_{ph} is the short circuit current

I_s is the reverse saturation current of diode (A),

q is the electron charge ($1.602 \times 10^{-19} C$),

V is the voltage across the diode (V),

K is the Boltzmann's constant ($1.381 \times 10^{-23} J/K$),

T is the junction temperature in *Kelvin* (K).

N Ideality factor of the diode

R_s is the series resistance of diode,

R_{sh} is the shunt resistance of diode,

Working backwards from the equations, an equivalent circuit can be easily determined, and this aids to the development of the simulation model. This equivalent circuit model is shown in Figure 1.

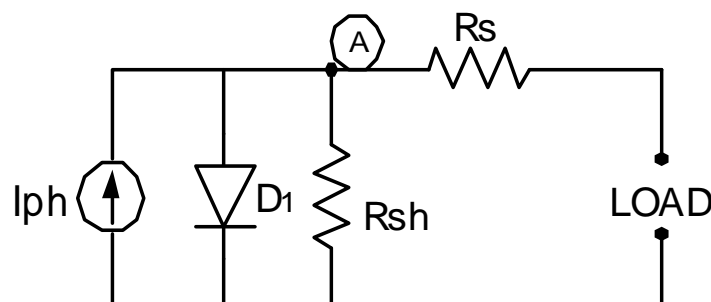


Figure 1. PV cell circuit model

The complete behaviour of PV cells are described by five model parameters (I_{ph} , N , I_s , R_s , R_{sh}) which is representative of the physical behavior of PV cell/module. These five parameters of PV cell/module are in fact related to two environmental conditions of solar insolation & temperature. The determination of these model parameters is not straightforward owing to non-linear nature of equation (1).

3. Solar cell: a diode perspective

Solar cells are photodiodes on a large scale and therefore have some basic characteristics of a junction diode. The nonlinearities in PV cell V-I characteristics is basically due to presence of this functional

device diode as prominently seen in circuit model of Figure 1. It is therefore logical to begin with a simulation study of four quadrant diode characteristics both under dark and also when illuminated.

A. Diode characteristics under dark

The schematic of Figure 1 is simulated for obtaining PV cell characteristics under dark and simulation result is shown in Figure 2(a). Under dark the photon generated current is zero. Obviously, the PV cell under Dark is a passive device and behaves like an ordinary diode.

The PV cell behavior under dark is thus the V-I characteristic curves of diode under forward and reverse bias conditions respectively. The noteworthy point here is that the device diode behaves with positive current and positive voltage in Ist-quadrant and with negative current and negative voltage in IIIrd – quadrant.

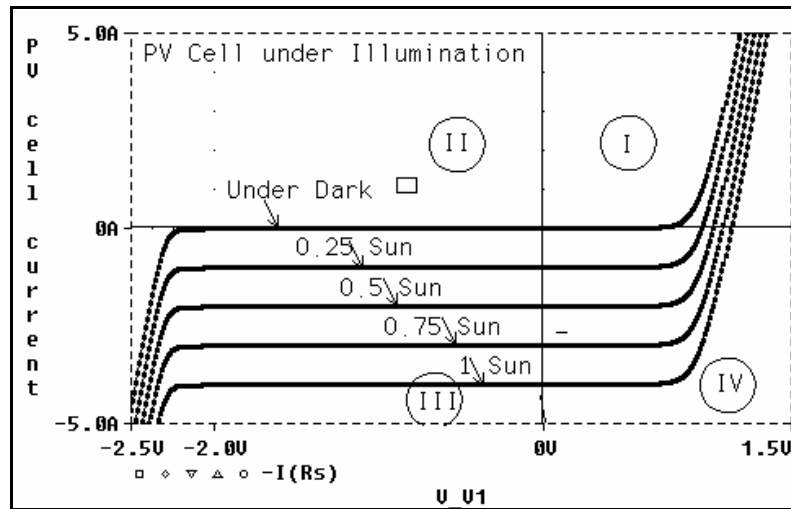


Figure 2. (a) PV cell characteristics under dark

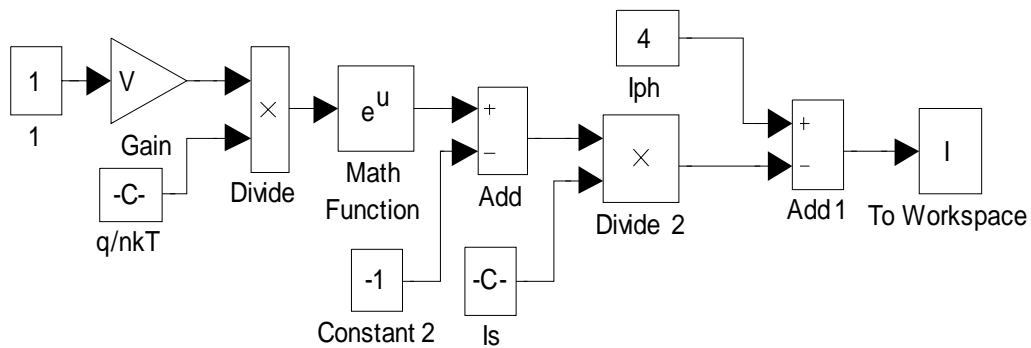


Figure 2. (b) Simulink model of PV cell

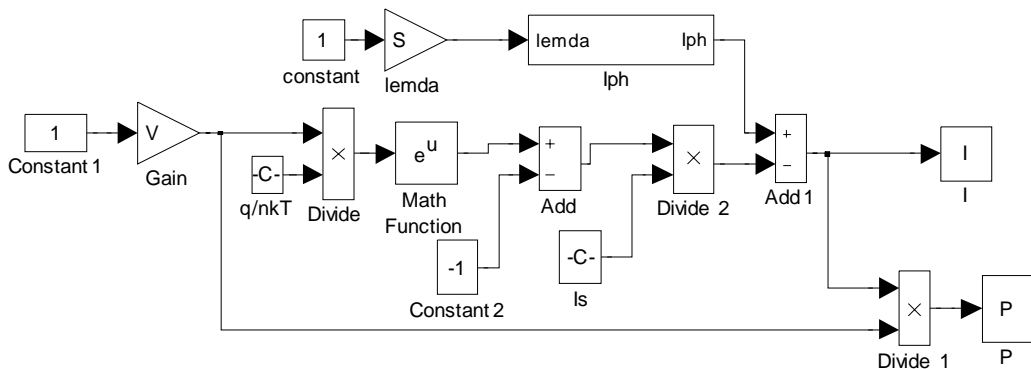


Figure 2. (c) Simulink model of PV cell for change in insolation

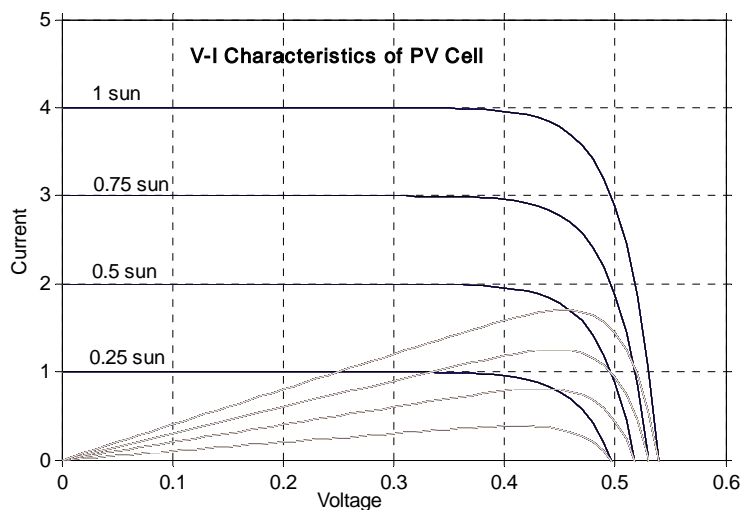


Figure 2. (d) PV cell characteristics for changing insolation

B. V-I characteristics of PV cell

The effect of reduced solar insolation is actually to shift diode characteristic curve downward along current axis as shown in Figure 2 (d). Equation (1) is simulated to plot V-I characteristic of the PV cell. The simulink model is as shown in Figure 2 (b). Here V is varied from 0 V to 0.7 V in steps. With slight modification in Figure 2 (b) i.e. Figure 2 (c) effect of change in insolation on V-I characteristic can be seen as shown in Figure 2 (d). The shifting of diode characteristic curve with increasing insolation along current axis reveals that current is proportional to incident sunlight while voltage capability of the cell is almost constant from high to very low light levels. This indeed enunciates the PV-cell behaviour is more like a current source than a voltage source and occurrence of PV-effect is in fourth quadrant only. Here it is noteworthy to see that cell generates both current and voltage and acts as a photovoltaic generator.

C. PV cell under Illumination

The effect of solar insolation (Illumination) on a PN junction can be studied by increasing the value of insolation from its zero value (for dark), to a value of 1000W/m^2 , a standard test condition for which its performance is specified and also termed as 100% solar radiation or 1 sun i.e. 1000W/m^2 . Since the photon generated current I_{ph} is directly proportional to solar insolation incident upon cell, a 0.75 times the value of rated I_{ph} will represent 75% of solar insolation or 0.75 suns. Similarly a value of 50% of rated I_{ph} will correspond to 50% and likewise.

Figure 2 (b) shows the simulink diagram for simulating the PV cell which is obtained by the mathematical representation of the pv cell eq.(1). On simulating the family of characteristic curves of Figure 2 (d) can be produced for varying insolation level by changing insolation level from 0.25 sun to 1 sun in steps of 0.25 using Figure 2 (c). The PV cell output is limited by the cell current and the cell voltage, and it can only produce a power with any combinations of current and voltage on the I-V curve. It also shows that the cell current is proportional to the irradiance.

4. Determination of V-I characteristics: experimental set up

Figure 3 (a) depicts scheme of measurement, which is used to obtain V-I characteristics of a PV module. Light source in the laboratory using an array of Dichroic halogen lamp (12V, 50W) whose distance with respect to PV module can be adjusted to get different level of Insolation. To get V-I characteristics of a PV module at different temperature, a circuit of tubes on rear side of module frame is distributed and controlled hot air is blown through to set desired temperature. Different sensors and signal conditioning unit are used to measure voltage, current, temperature and solar Insolation of the PV module.

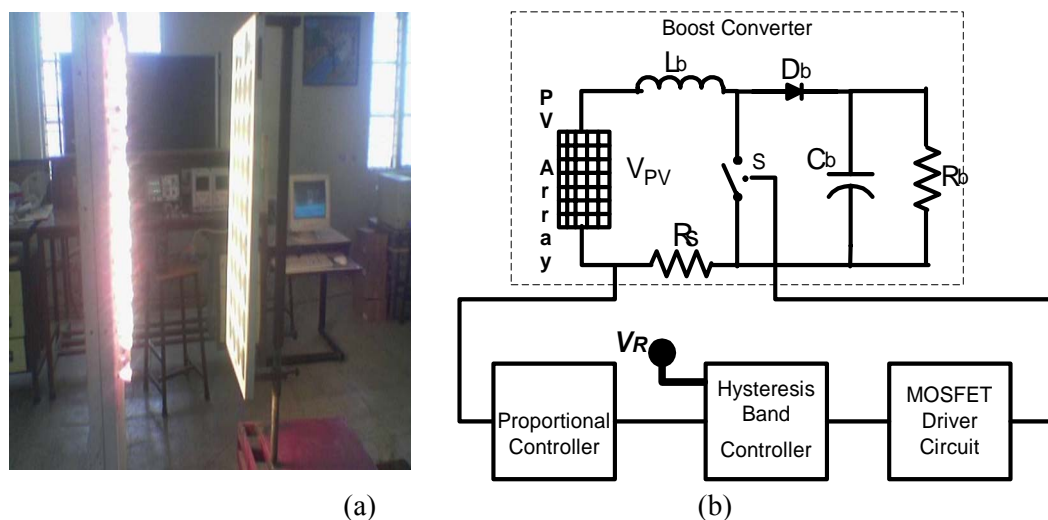


Figure 3. (a) Experimental set up, and (b) PV loading circuit

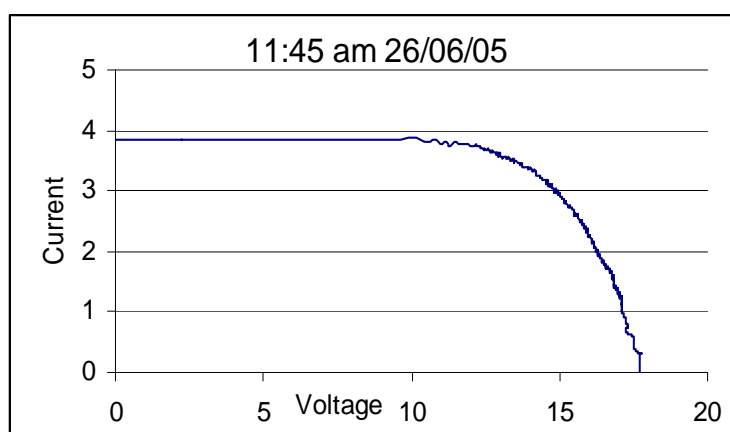


Figure 3. (c) Experimentally obtained V-I characteristics of PV module

A DC to DC boost converter shown in Figure 3 (b) is used to load PV array electrically. The arrangement makes use of PC controlled incremental loading of solar module and scans through its V-I characteristics. As PV module is loaded, current drawn from PV panel increases and its voltage falls down as is obvious from V-I characteristics of a PV cell in Figure 2 (d). The reference voltage V_R is generated through a 12 bit DAC of Data acquisition card for loading of PV array. By varying V_R , one can load PV module from open circuit to short circuit and V-I characteristics of module can be scanned through. The computer using data acquisition card and program written in 'C' language; acquires data of voltage, current, solar insolation and temperature for corresponding value of V_R . The data file stores data in suitable format to be used with MS excel program for plotting the V-I characteristics of the PV module. One such characteristic is shown in Figure 3 (c).

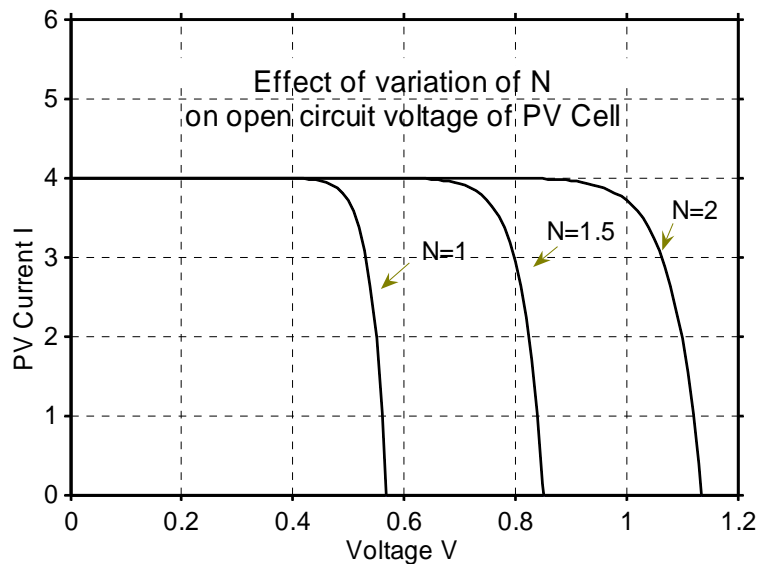


Figure 4. (a) PV cell characteristics with varying 'N'

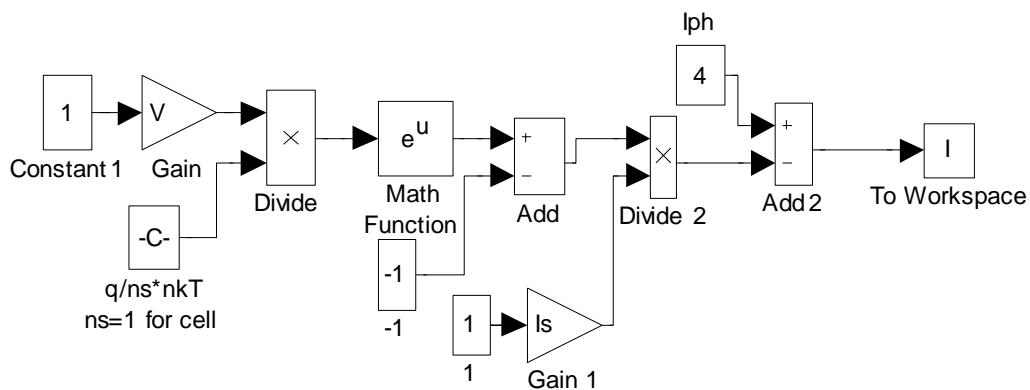


Figure 4. (b) Simulink model of PV cell for change in saturation current

5. Model parameter variation

The circuit model of Figure 1 readily offers an investigation in variation of five model parameter of which two parameters I_s & N are related to Diode model, one parameter I_{ph} is related to light or photon generated current and resistance R_s and R_{sh} represent various losses in PV cell. In this section, effect of variation of these five parameters and their influence on V-I graph of PV Cell is studied using Simulink.

A. Diode Parameter (I_s & N) Variation

With slight modifications simulink model of Figure 4 (b), is used to draw the V-I characteristic with changing value of N . Equation (1) is simulated for three different values of N . Figure 4 (a) shows 'V-I characteristics' of a PV cell for three different values of N corresponding to 1, 1.5 & 2 respectively. The ideal value of Ideality -factor ' N ' is unity but its practical value for Silicon PV cell lies between 1 & 2. It can be observed that as we increase value of N , the open circuit voltage of cell increases, and this fact may effectively be used in simulation of a PV module, which is a congregation of many cells in series.

Another important model parameter which reflects variation in V-I characteristics of PV cell is diode reverse saturation current I_s . The simulated graph of Figure 4(c) shows 'V-I characteristics' of PV cell for three different values of I_s corresponding to 100nA, 10 μ A, and 1 μ A. The effect of increasing I_s is obviously seen as corresponding decrease in open circuit voltage.

B. Variation in R_s

The PV cell model of Figure 1 has two loss representative element R_s and R_{sh} . The effect of increasing value of R_s can be seen using simulink model produced for equation (1). The main variable is control

voltage V and another variable is introduced in the feedback as R_s . The simulation is produced for three different values of R_s as 0.001Ω , 0.01Ω , and 0.1Ω . The resultant V-I characteristics and power-curves is obtained as shown in Figure 4 (d). The series resistance (R_s) of the PV module has a large impact on the slope of the I-V curve near the open-circuit voltage (V_{oc}), as shown in the graph. One can observe decay of PV cell constant current characteristics at an early cell voltage for higher value of R_s , indicating more output power loss.

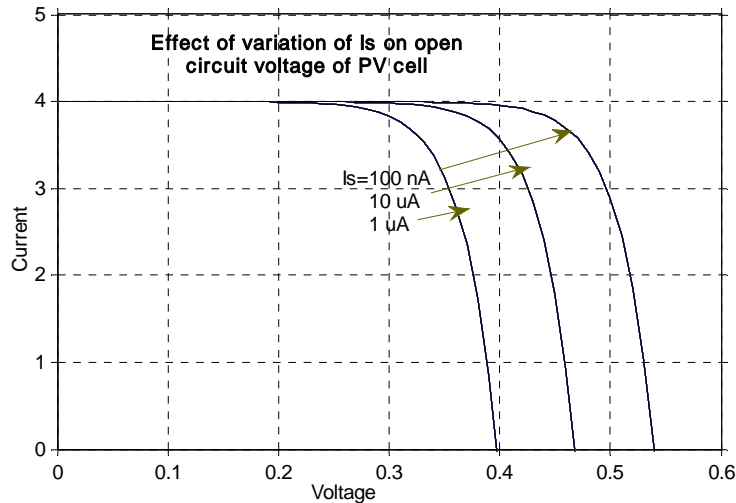


Figure 4. (c) PV cell characteristics with varying 'Is'

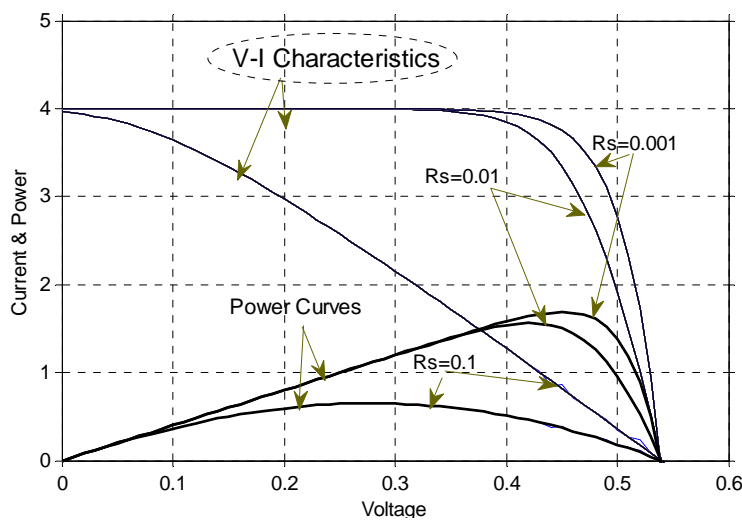


Figure 4. (d) PV cell characteristics with varying 'Rs'

The power curves demonstrate that higher value of R_s reduces power output of a cell. An indicative index known as 'Fill factor' in PV terminology is defined for judgment of efficient cell operation as given by (2):

$$FF = \frac{P_{\max}}{V_{oc} \cdot I_{sc}} \quad (2)$$

The fill factor appreciably gets low for higher value of R_s .

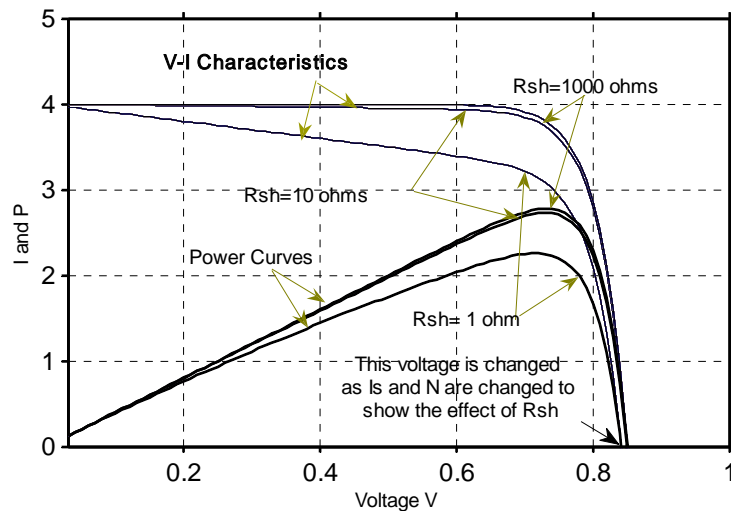


Figure 4. (e) PV cell characteristics with varying ‘Rsh’

C. Variation in R_{sh}

The effect of varying R_{sh} of a PV cell under Simulink can be produced in the same way as is done for varying R_s . The varying parameter is now R_{sh} in place of R_s . The simulation is produced for three different values of R_{sh} ; 1k Ω , 100 Ω & 10 Ω . The resultant V-I characteristics & power-curves plotted is shown in Figure 4 (e). It is observed that the smallest value of R_{sh} causes PV cell current to fall more steeply indicating higher power loss and low Fill Factor.

All practical PV cell therefore must have high value of R_{sh} and low value of R_s for giving more output power and higher Fill Factor.

6. Environmental parameter variation

A. PV Cell under Reduced Insolation

The two environmental conditions of Solar Insolation and Temperature govern output of a PV Cell. Simulink is used to demonstrate behavior of PV cell under varying solar insolation. The schematic used for the purpose is same as shown in Figure 2 (c).

The photon generated current I_{ph} is in fact related with solar insolation λ as

$$I_{ph} = [I_{sc} + k_I(T - 298)] \frac{\lambda}{100} \tag{3}$$

$K_I = 0.0017 \text{ A/}^\circ\text{C}$ is cell’s short-circuit current temperature coefficient, I_{sc} is cells short circuit current at 25 $^\circ\text{C}$, T is the cell’s temperature and λ is the solar insolation in kW/m 2

From equation (3), it can be seen that at constant temperature, the photon generated current ‘ I_{ph} ’ is directly proportional to solar insolation. If now the rated ‘ I_{sc} ’ of specimen PV cell is 4A under STC (solar insolation of 1 sun at 25 $^\circ\text{C}$), i.e. 1000 W/m 2 insolation. Then insolation of 0.75, 0.5 & 0.25 Sun (at 25 $^\circ\text{C}$) can accordingly be set by setting insolation variable λ .

The effect of varying solar insolation on V-I characteristics can now be produced using Simulink where the main variable is control voltage V and other variable is insolation. The simulation is produced for five different values of solar insolation from zero to 1 sun in steps of 0.25 sun. The resultant V-I characteristics and power- curves is shown in Figure 5 (a).

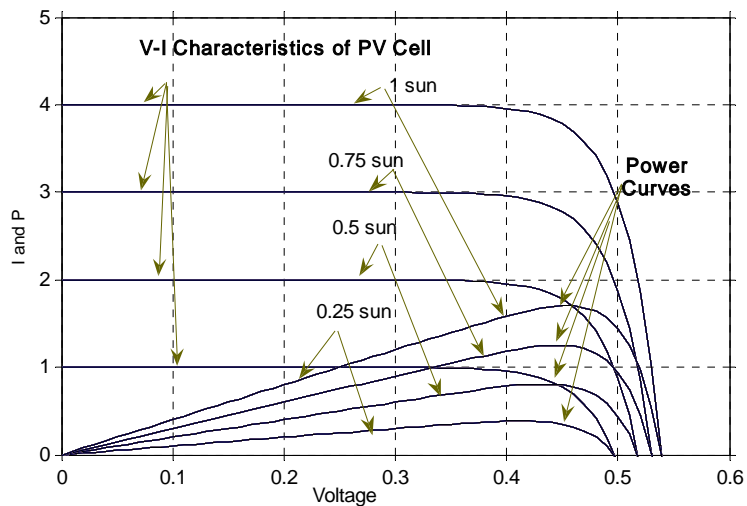


Figure 5. (a) PV cell characteristics with varying ‘insolation’

From the simulation result it can be observed that as solar radiation falling on PV cell is reduced, both I_{sc} and V_{oc} decreases, but the change in V_{oc} is not as prominent with incident solar radiation as is with I_{sc} , which varies almost directly proportional.

B. PV Cell under Varying Temperature

The effect of varying temperature on PV cell output is two fold: (i) It affects short circuit current ‘ I_{sc} ’ of Cell as given by equation (3). (ii) It changes saturation current of the diode in PV cell approximately as cubic power and is given by equation (4),

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

$T_{nom} = 273^\circ\text{K}$, I_s is cell’s reverse saturation current, E_g is band gap energy of the semiconductor and V_t is thermal voltage at room temperature.

Obviously from (4) the saturation current of diode of PV cell is highly temperature dependent and it increases with increase in temperature and is taken care by Simulink diode model. The increased saturation current in fact reduces open circuit voltage as discussed in section V.

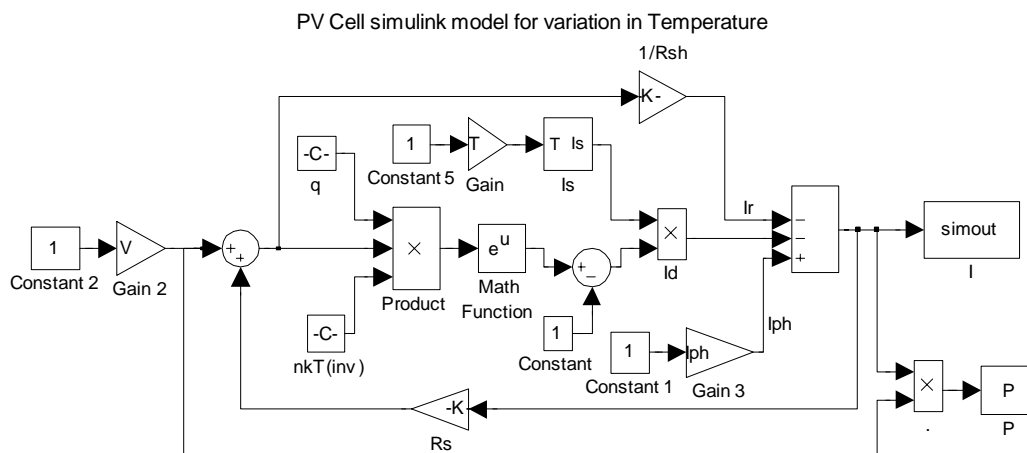


Figure 5. (b) Simulink model of PV cell for change in temperature

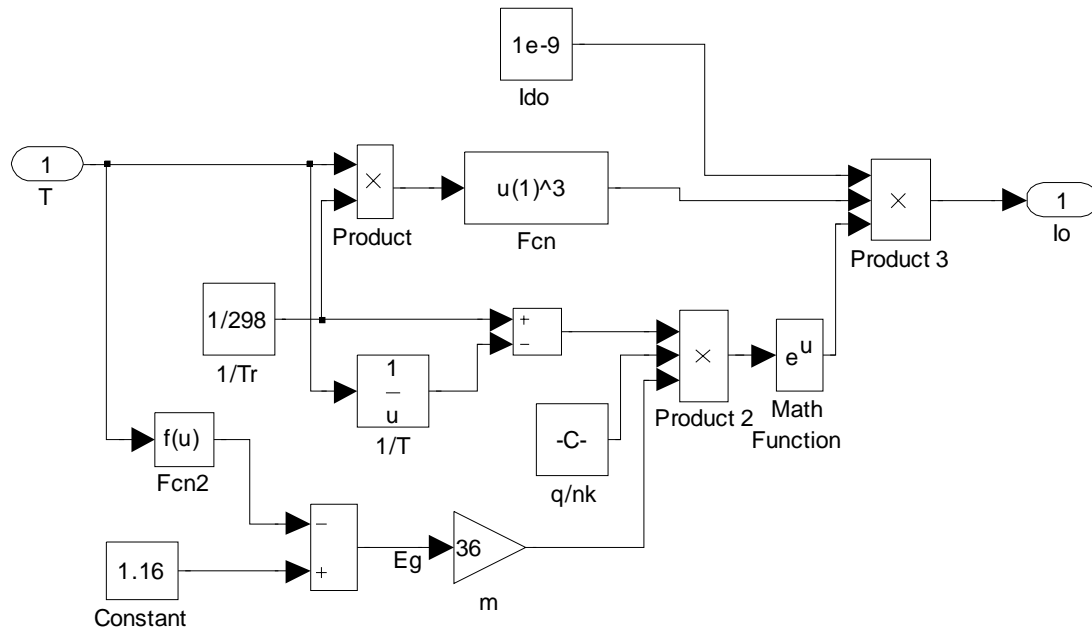


Figure 5. (c) Internal schematic of subsystem I_s

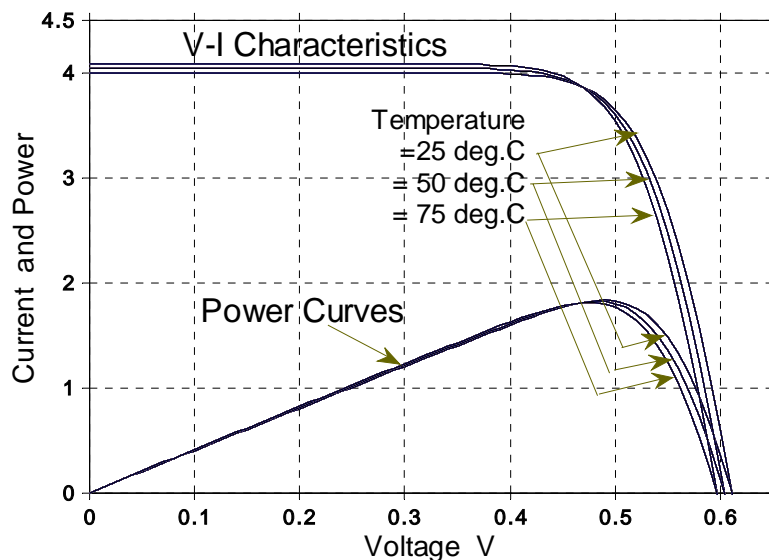


Figure 5. (d) PV cell characteristics & power curves with varying temperature

To study the effect of Temperature variation on PV cell output, temperature is taken as one of the variable in addition to the voltage. V-I characteristics and power curves are obtained as shown in Figure 5 (d) after simulation of Figure 5 (b). Figure 5 (c) show the detailed diagram of subsystem I_s which is obtained after simulating equation (4).

7. PV module and array characteristics

A solar photovoltaic module is a congregation of solar PV cells in series so as to produce a compatible voltage to charge a standard battery of 12 volts. A stand-alone PV cell generates a voltage in the range of 0.5-0.6 volts and has non-linear voltage-current relationship as given by (1). Uptill now the focus of the study was basic unit a PV cell. To carry out simulation study of a PV module; the PV Cell voltage-current relationship in eq. (1) is modified for PV Module by neglecting R_s & R_{sh} and is now given as eq. (5).

$$I = n_p \cdot I_{ph} - n_p I_s \left(\exp \frac{qV}{(N.K.T).n_s} - 1 \right) \tag{5}$$

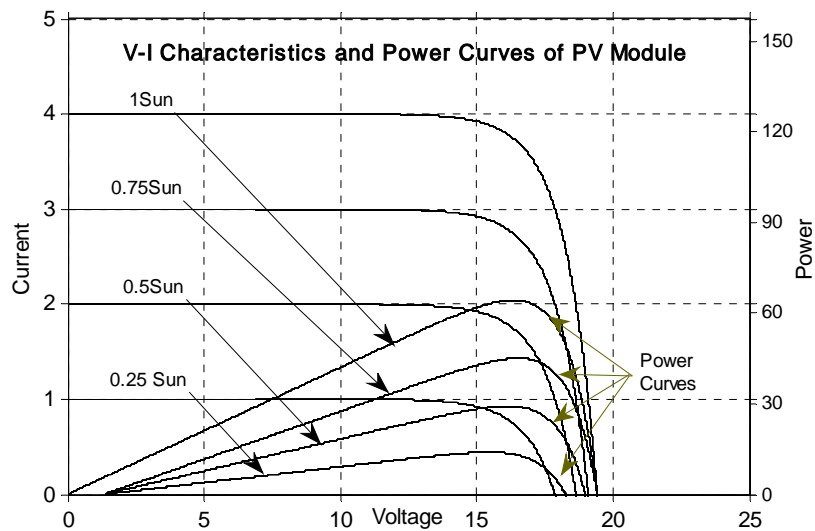


Figure 6. PV module characteristics & power curves for varying insolation

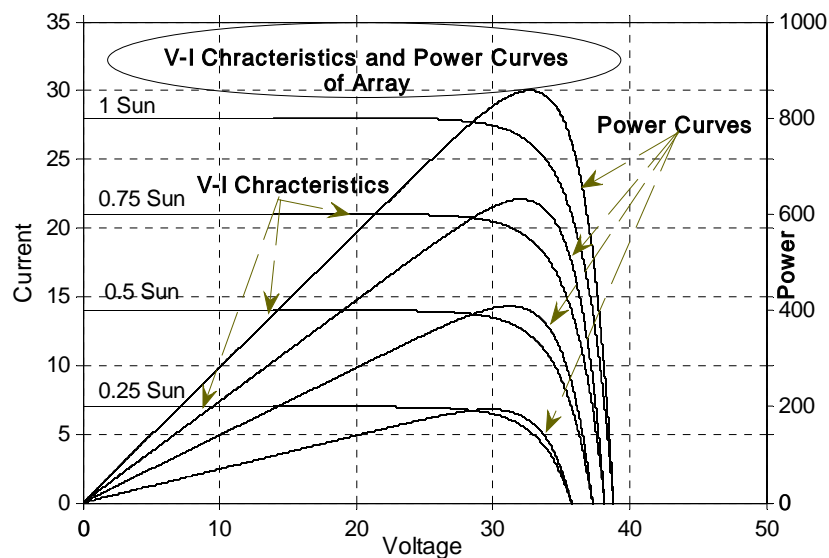


Figure 7. PV array characteristics and power curves for varying insolation

In a PV module there is only one path available for conduction of current as all the cells are connected in series, therefore $n_p = 1$. The number of series connected cells in the PV module which is used for experimental work here is 36 hence n_s is taken as 36. Hence PV module simulation study is identical with the PV cell study and the schematic of Figure 2 (c) can be used to simulate the characteristic of a PV module after introducing n_p and n_s at the appropriate places.

With this formulation, the simulation result of a PV module is shown in Figure 6 for $I_s = 100\text{nA}$. The plots are very much identical to Figure 5 (a), with the exception that V_{oc} is higher and now represent characteristics for a PV module than for a PV cell.

PV array can be simulated in a similar manner by making a slight change in the equation and simulink model by putting $n_p = 7$ and $n_s = 72$. As there are two modules connected in series and seven such series connected pairs are connected in parallel to form an array. The simulated graph is shown in Figure 7.

8. Maximum power point tracking

A plot of dP/dV is shown in Figure 8. The intersection of the dP/dV graph on voltage axis i.e. X-Axis gives the voltage corresponding to peak or maximum power of the PV module (since at voltage axis, the $dP/dV=0$). The Value of dP/dV is negative on the right side of the MPP and positive on the left side.

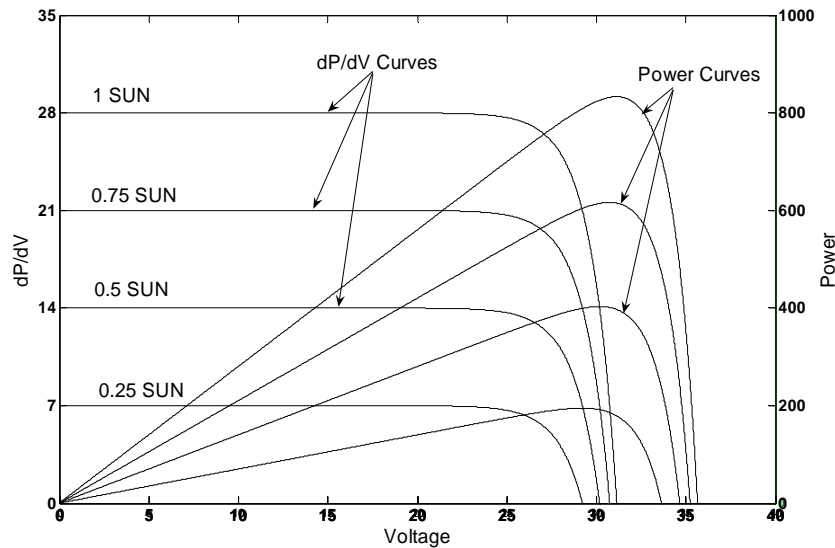


Figure 8. Array power-curves and dP/dV curves for varying insolation

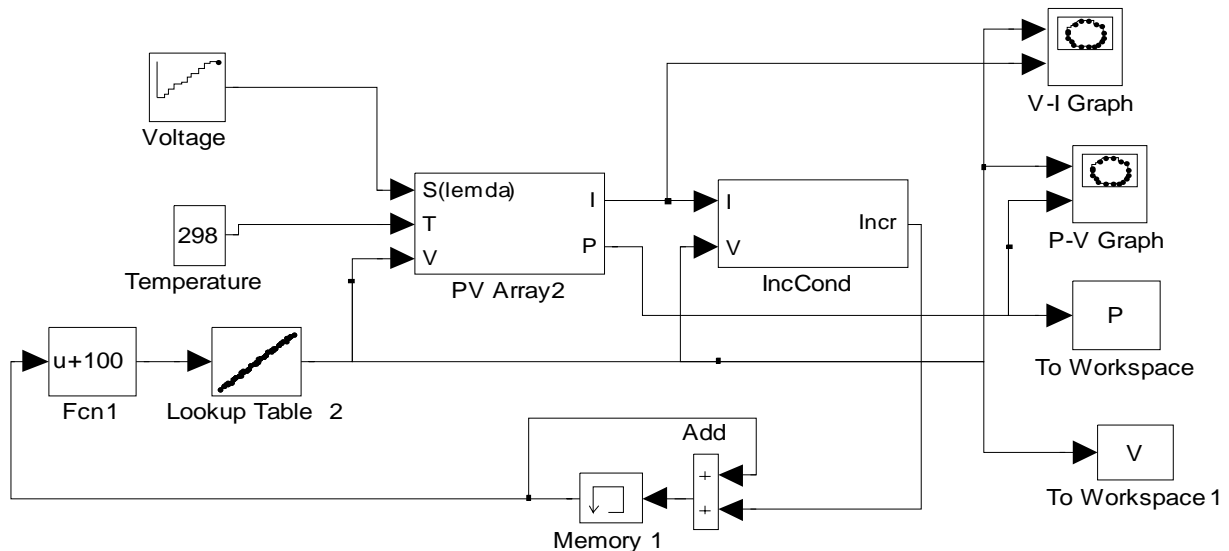


Figure 9. Maximum power point tracking of PV array by IncCond algorithm

Many Maximum power point techniques and algorithms are available in Literature which can locate MPP such that $dP/dV=0$ at any given instant and environmental conditions of Solar Insolation and Temperature [6, 7]. First individual simulink models are developed using the flow chart for each algorithm. Then in the next step the algorithms are used for PV array to operate at MPP under changing insolation and varying temperature thereafter. The control diagram of the system for simulating MPPT algorithm is shown in Figure 9. Figure 10 gives the detailed simulink model of incremental conductance algorithm.

IncCond Method is described here for reference. Voltage and current of the PV array are the input to the IncCond model of mppt algorithm. Output of IncCond block is sent to lookup table of voltage. The output of the look up table is feeded back to PV array. A matlab function block (u+100) is added to make the voltage around 29V for fast locating MPP. The reason being that normally maximum power occurs at around 70% to 80% of V_{oc} which is around 29V for the panel under consideration. PV array is receiving insolation and temperature as input. Here in this simulation temperature is kept constant and insolation is varied from 100 W/m^2 to 1000 W/m^2 in steps of 100. The simulated result shows the feasibility of the tracking algorithm as shown in Figure 11. Maximum power tracked is 857.4 W, voltage =32.5V with an oscillation from 849.5 W to 852.9 W at an insolation of 1000. For an insolation of 700 W/m^2 maximum power tracked is equal to 585.9 W, voltage = 32V with an oscillation from 582.1W to 579.9 W.

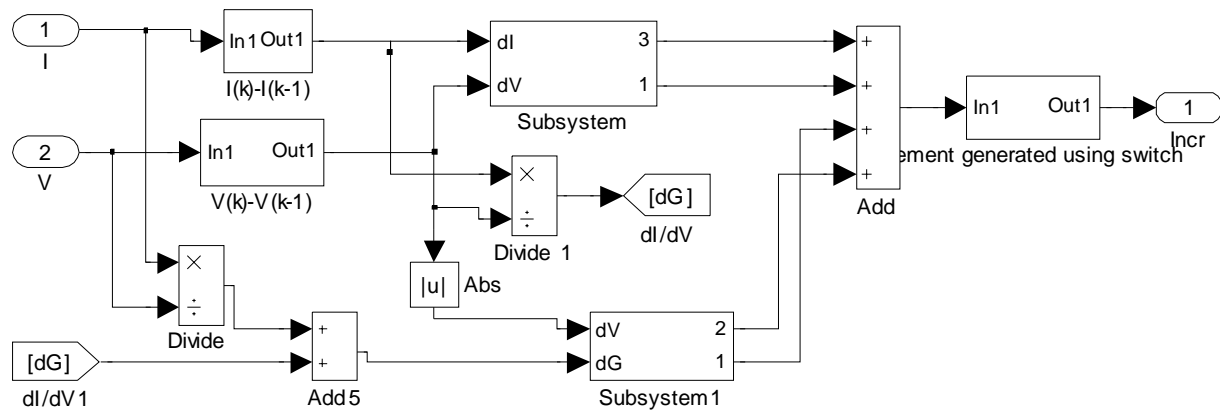


Figure 10. Simulink model of incremental conductance algorithm

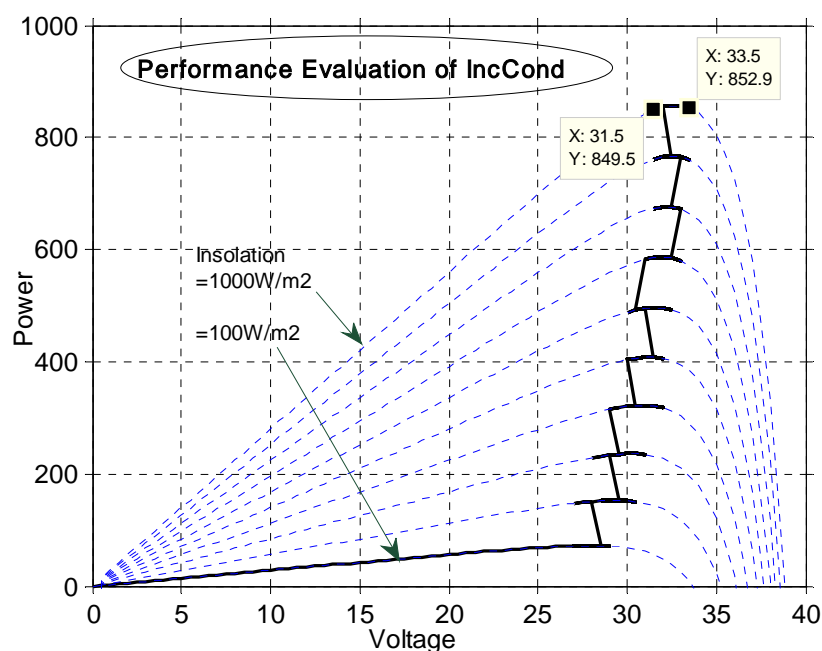


Figure 11. Maximum power point tracking by IncCond for varying insolation

9. Conclusion

A Photovoltaic system not only consist of PV modules but also involves good deal of power electronics as an interface between PV modules and load for effective and efficient utilization of naturally available Sun power. Such a PV model is easy to be used for the implementation on Matlab/Simulink modelling and simulation platform. Specially, in the context of the SimPower-System tool, the PV model can be used for the modelling and analysis in the field of solar PV power conversion system. The purpose of using Simulink for simulation is that system study as a whole can be undertaken as it can simulate both PV modules and the associated power electronics under different operating conditions and load.

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Savita Nema is Associate Professor at the Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal, India. She received her Bachelors degree in Electrical Engineering and Masters degree in Control Engineering from Rani Durgavati University, Jabalpur India. Her current research focuses on Residential Photovoltaic Energy Storage System and its Modeling.
E-mail address: s_nema@yahoo.com



R. K. Nema received his PhD degree in Electrical Engineering from Barkatullah University, Bhopal, India in 2004. He is currently Associate Professor at the Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal, India. His current research interest include power conditioning unit for Renewable Energy storage system particularly Solar Energy, Hybrid Energy Systems, Grid Interconnection of Renewable Energy sources.
E-mail address: rk_nema@yahoo.com



Gayatri Agnihotri is a Professor at the Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal, India. She received her PhD in System Engineering from Indian Institute of Technology, New Delhi, India. Her current research focuses on Modeling of Hybrid Energy Systems. Her current research area are Modeling of Hybrid Energy Systems and power system.
E-mail address: gayatri1@rediffmail.com