

Computer Simulation Based Study of Photovoltaic Cells/Modules and their Experimental Verification

R.K. Nema¹, Savita Nema¹, and Gayatri Agnihotri¹

¹Department of Electrical Engineering, MANIT, Bhopal, INDIA

Email: rk_nema@yahoo.com, s_nema@yahoo.com, gayatri1@rediffmail.com

Abstract—A computer simulation based study of photovoltaic cells/ modules using circuit simulator PSpice is presented in this paper. The PSpice is an analogue/digital circuit simulator which calculates voltage and current in a circuit under variety of different circumstances. This feature of PSpice is used to simulate a circuit based model for PV cells/ modules and then to conduct behavioral study under varying conditions of solar insolation including shading effect, temperature, diode model parameters, series and shunt resistance etc. The study is very helpful in clearly outlining the principles and the intricacies of PV cells/modules and may surely be used to verify impact of different topologies and control techniques on the performance of different types of PV system. To put the simulation study on firm footing an experimental verification is also carried out in the Lab by developing a PC based data acquisition system, which is also briefly discussed here as subsidiary.

Index Terms— Circuit Simulator, Diode model parameters, Insolation, PSpice, PV Cells/modules, Shading

I. 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]. 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. The Simulator used therefore should be able to model not only PV cells/modules but also have the capability to simulate associated power electronics so that a simulation of a complete PV system can be carried out [4]. The purpose of using PSpice 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.

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 system as per the system requirement of voltage and the current. From this point of view the present paper deals with the simulation study of both PV cells; a basic unit, and PV modules; a commercially available unit of Photovoltaics.

II. 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 behavior of the PV cell. A double exponential equation may be used for the polycrystalline Silicon cells [4].

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

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

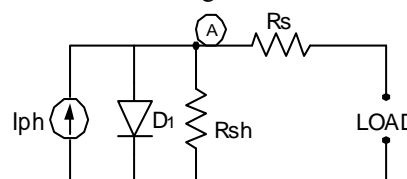


Fig.1: PV Cell circuit model

The complete behavior of PV cells are described by five model parameters (I_{ph} , N , I_s , R_s , R_{sh}) which is representative of a physical PV cell/module [4]. These five parameters of PV cell/module are in fact related to two environmental parameters of solar insolation & temperature and owing to non-linear nature of equation (1) their determination is not straightforward.

III. SOLAR CELL: A DIODE PERSPECTIVE

Solar cells are photodiodes on a large scale and therefore have some basic characteristics of a pn junction diode. The nonlinearities in PV Cell V-I characteristics is basically due to presence of device diode in circuit model

R.K. Nema, Asst.Professor is with the Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal-462051, India (Email: rk_nema@yahoo.com).

of Fig. 1. It is therefore logical to begin with four quadrant study of diode characteristics under dark and also when illuminated. The circuit simulator PSpice is used as an effective tool to carry out such behavioral examination and the schematic used for this purpose is shown in Fig. 2(a).

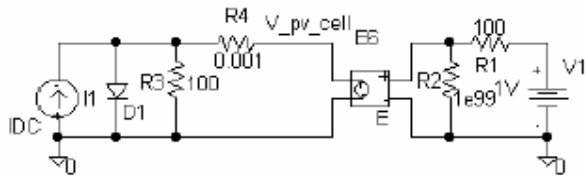


Fig.2(a): Schematic for generating diode curve both under dark and when illuminated.

A. Diode Characteristics under dark

The schematic of Fig. 2(a) is simulated for obtaining PV Cell characteristics under Dark and simulation result is shown in Fig. 2(b). Under Dark the photon generated current is zero which under PSpice is achieved by setting 'value' attribute of Spice source IDC as zero. Obviously, the PV cell under Dark is a passive device and behaves like an ordinary diode.

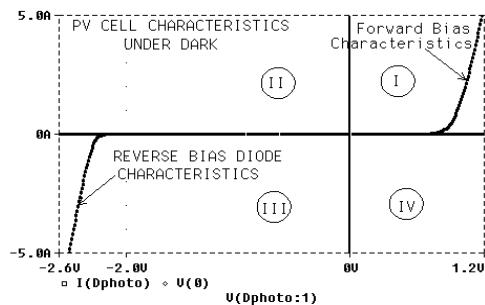


Fig. 2(b): PV Cell Characteristics under Dark

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.

B. PV Cell Under Illumination

The effect of solar insolation (Illumination) on a PN junction can be studied by increasing the value of source current Idc in Fig. 2(a) from its zero value (for dark), to a value of 4 amp, taken to be an equivalence of 100% solar radiation or 1 sun. Since the photon current I_{ph} or equivalent Idc, is directly proportional to the incident solar insolation, a value of 3Amp will represent 75% or 0.75 sun, a value of 2 Amp will correspond to 50% and likewise. The family of characteristic curves of Fig 2(c) can be produced for varying insolation level under PSpice by "dc sweep" analysis of voltage source V1.

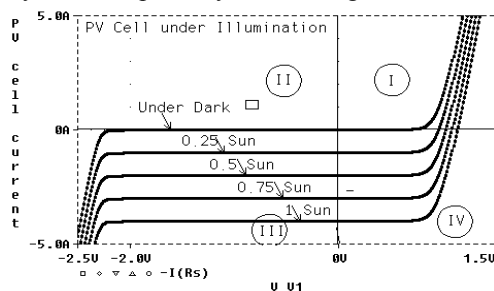


Fig. 2(c): PV cell characteristics under illumination

C. V-I Characteristics of PV Cell

The effect of solar insolation is actually to shift diode characteristic curve downward along current axis; making it to operate in IVth-quadrant as shown in Fig. 2(c). 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 very low light levels. This behavior indeed enunciates that a PV-cell behaves more like a current source than a voltage source, and also PV-effect occurs in fourth quadrant only. Here it is noteworthy to see that cell generates both current and voltage and acts as a photovoltaic generator. Thus, the fourth quadrant portion of diode characteristic curve is called V-I curve of PV cell in solar photovoltaic terminology. To produce a solar cell V-I curve, the fourth quadrant of characteristics curve is flipped vertically about the voltage axis into the Ist quadrant as shown in Fig. 2(d). This is done so that the current direction is positive rather than negative. This is strictly in accordance with the convention that a generator must source positive current from its positive terminal.

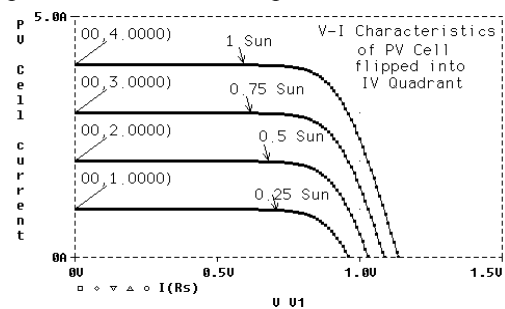


Fig. 2(d): PV Cell Characteristics

IV. DETERMINATION OF V-I CHARACTERISTICS: EXPERIMENTAL SET UP

Fig. 3(a) depicts scheme of measurement, which is used to obtain V-I characteristics of a PV module. Light source in the laboratory is 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.

A DC to DC boost converter with hysteresis band current control is used for loading of PV array as shown in Fig. 3(b). The arrangement makes use of PC controlled 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 Fig. 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 characteristics is shown in Fig. 3(c).

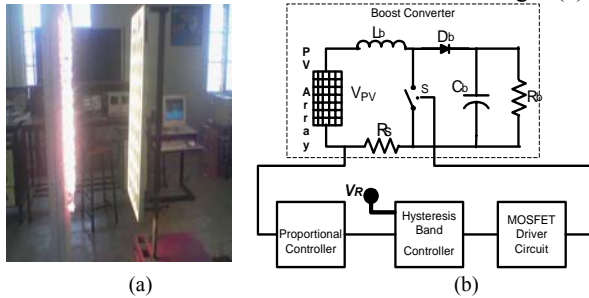


Fig. 3(a): Experimental set up (b): PV Loading Circuit

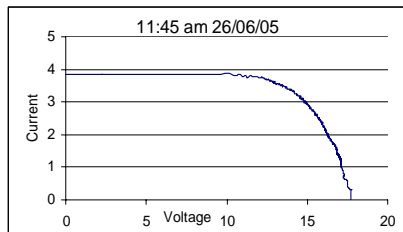


Fig. 3(c): Experimentally obtained V-I Characteristics of PV Module

V. MODEL PARAMETER VARIATION

The circuit model of Fig. 1 readily offers an investigation in variation of five model parameter of which two I_s & N are related to Diode model, one 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 circuit simulator PSpice.

A. Diode Parameter (I_s & N) Variation

Fig. 4(a) shows 'V-I characteristics' of a PV cell for three different values of N corresponding to 1, 1.5 & 2 respectively. Obviously, as we increase value of N , it takes more sweep voltage to completely scan its V-I characteristics. 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. The plot of Fig. 4(a) is obtained by 'nested-sweep' feature of 'DC-Sweep' analysis where voltage source V1 in Fig. 2(a) is main sweep variable and diode model parameter N is a nested sweep variable.

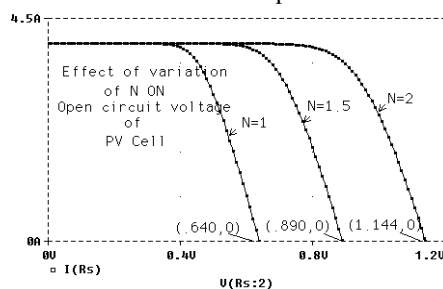


Fig. 4(a): PV Cell Characteristics with varying ' N '

Another important model parameter which reflects

variation in V-I characteristics of PV cell is diode reverse saturation current I_s . The simulation graph of Fig. 4(b) shows 'V-I characteristics' of PV cell for three different values of I_s corresponding to 100nA, 1μA, and 10μA. Obviously the effect of increasing I_s is seen in corresponding decreased open circuit voltage. The plot of Fig. 4(b) is obtained by 'nested-sweep' feature of 'DC-Sweep' analysis where voltage source V1 in Fig. 2(a) is main sweep variable and diode model parameter I_s is now the nested sweep variable.

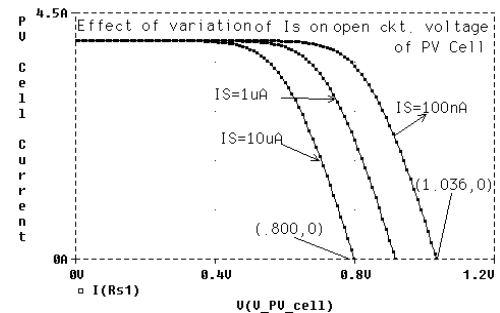


Fig. 4(b): PV Cell Characteristics with varying ' I_s '

A combined effect of varying N & I_s on ' V_{oc} ' is shown in Fig. 4(c), where open circuit voltage ' V_{oc} ' of PV cell is plotted as a function of N , taking I_s as a parameter. The smallest value of I_s produces largest open circuit voltage for same ideality factor N . To produce such a clan of graph under PSpice the schematic of Fig. 2(a) is first capacitive loaded and then simulated for $N=0.1$ to $N=30$ in steps of 0.01 using DC sweep/model parameter analysis, for one particular value of I_s . The above step is now repeated for other values of I_s and data files are then appended together to generate such family of the curves of Fig. 4(c). This is a linear graph with a little bit of offset corresponding to $N=0.1$. The value of $N=0$ will set a very high value of current in (1), causing PSpice convergence problem.

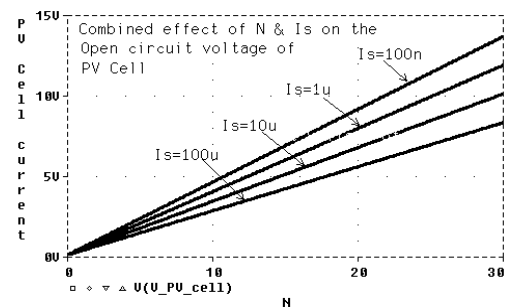
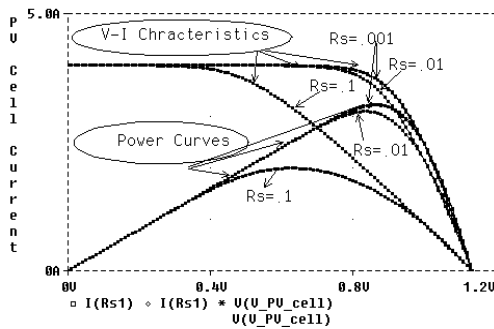


Fig. 4(c): PV Cell Characteristics with varying ' I_s ' & N .

B. Variation in R_s

The PV cell model of Fig. 1 has two loss representative component R_s and R_{sh} . The effect of increasing value of R_s can be seen under PSpice by 'Nested DC-sweep' analysis. The main sweep variable is a control voltage V1 in Fig. 2(a) and nested sweep variable is 'global' parameter 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 using post processor 'Probe' is obtained as shown in Fig. 4(d). 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.

Fig. 4(d): PV Cell Characteristics and power curves for varying R_s .

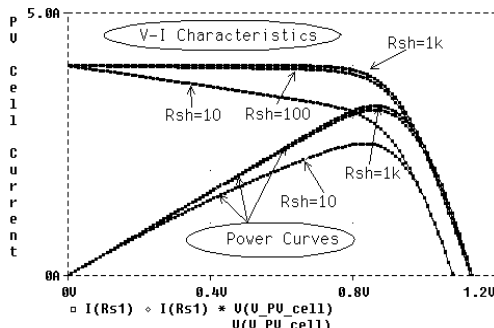
The power curves demonstrate that higher value of R_s reduces power output of a cell. An indicative index known as 'Fill factor' in PV terminology is defined for judgment of efficient cell operation as given by (2):

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

The fill factor appreciably gets low for higher value of R_s and can be calculated under Probe window.

C. Variation in R_{sh}

The effect of varying R_{sh} of a PV cell under PSpice can be produced in the same way as is done for varying R_s . The Global 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 using post processor 'Probe' is shown in Fig. 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.

Fig. 4(e): PV Cell Characteristics and power curves for varying R_{sh} .

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

VI. ENVIRONMENTAL PARAMETER VARIATION

A. PV Cell Under Reduced Insolation

The two environmental conditions of Solar Insolation and Temperature govern output of a PV Cell. The circuit simulator PSpice is used to demonstrate behavior of PV cell under varying Solar Insolation. The schematic used for the purpose is same as shown in Fig. 2(a). The photon generated current I_{ph} is in fact related with solar insolation λ as in (2):

$$I_{ph} = [I_{SCR} + K_I (T - 298)] \frac{\lambda}{100} \quad (3)$$

Where, $K_I = 0.0017 \text{ A}^\circ\text{C}$,

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°C), then declining values of current's such as 3, 2 & 1A will represent solar insolation's of 0.75, 0.5 & 0.25 Sun (at 25°C) respectively and can accordingly be set by setting value attribute of current source I_{ph} in Fig. 2(a).

The effect of varying Solar Insolation on V-I characteristics can now be produced using 'Nested DC-sweep' analysis, where the main variable is control voltage V_1 and nested sweep variable is 'current source' I_{ph} . The simulation is produced for five different values of photon generated current ' I_{ph} ' representing varying solar Insolation from zero to 1 sun in steps of 0.25 sun. The resultant V-I characteristics and power-curves is shown in Fig. 5(a).

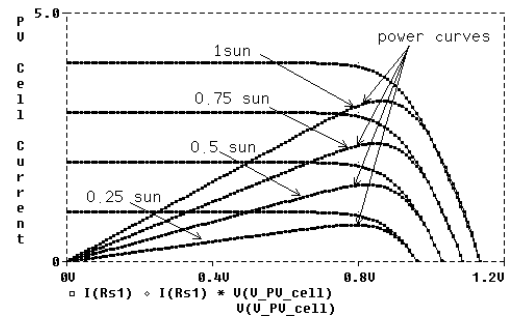


Fig. 5(a): PV Cell Characteristics and power curves for varying Insolation.

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 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 (3) (ii) It changes saturation current of the diode in PV cell approximately as cubic power and is given by (4),

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

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 Spice diode model. The increased saturation current in fact reduces open circuit voltage as discussed in section VI.

To study the effect of Temperature variation on PV Cell output, a modified version of the schematic of Fig. 2(a) will have to be used. This is because the photon generated current ' I_{ph} ' in Fig. 2(a) is temperature independent and therefore can not describe the temperature dependency of equation (3). To include this temperature dependency the analog behavioral modeling (ABM) feature of PSpice is used. The ABM block first simulates (3) and produces temperature dependent voltage as shown in Fig. 5(b). This output voltage of ABM block then drives a voltage controlled current source with unity gain producing a temperature

dependent current as desired for simulation of (3).

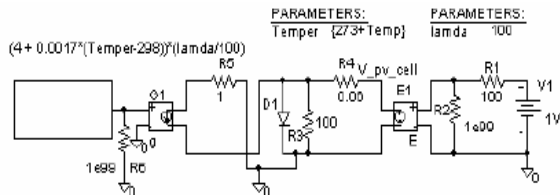


Fig. 5(b): Schematic for PV Cell Characteristics at varying Temperature.

The simulation result is shown in Fig. 5(c). The Simulator plot the behavior of the PV cell under three different temperatures of 27°C, 57°C and 87°C using Temperature sweep. It can be observed from simulation result that short circuit current of a PV Cell increases with increasing temperature and at the same time its open circuit voltage decreases.

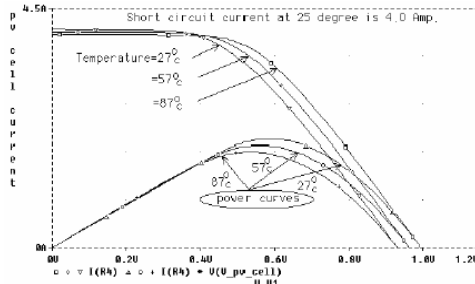


Fig. 5(c): PV Cell Characteristics and power curves for varying Temperature.

The net effect with increasing temperature of the cell is in decreased power output as reduction in open circuit voltage is more prominent than enhancement in short circuit current. The schematic uses dc sweep and temperature analysis to produce such family of the curves of Fig.5(c).

VII. PV MODULE 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 (1) is modified for PV Module by neglecting R_s & R_{sh} and is now given as (5).

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

In a PV module there is only one path available for conduction of current as all the cells are connected in series, therefore $n_p=1$. Thus the number of series connected cells n_s may now be combined with 'Ideality factor N ' of a unit PV cell for simulation study and in fact can simulate a PV module if the new value of Ideality factor ' N ' for module is as many times greater as the no. of PV cells connected in series. This fact of increasing ' V_{oc} ' with ' N ' has already been studied in section VI.

This is now an established fact that PV module simulation study is identical with the PV Cell study and the schematic in Fig. 2(a) can be used with renewed value

of diode model parameter N & I_s for a compatible voltage generation of a PV module.

With this formulation, the simulation result of a PV module is shown in Fig. 6 for $N=20$ & $I_s=14.11nA$. The plots are very much identical to Fig. 5(a), with the exception that V_{oc} is higher and now represent characteristics for a PV module than for a PV cell.

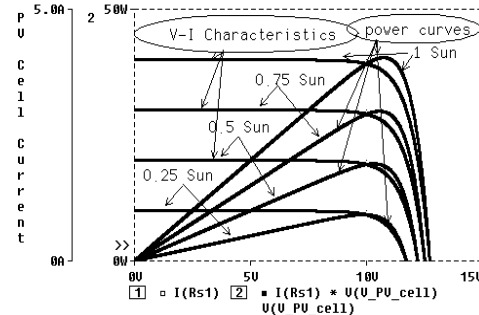


Fig. 6: PV module Characteristics & power-curves for varying Insolation.

VIII. MAXIMUM POWER POINT TRACKING

On the simulation result of Fig.6, a plot of dP/dV using derivative function of the Probe window is drawn as shown in Fig. 7. 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.

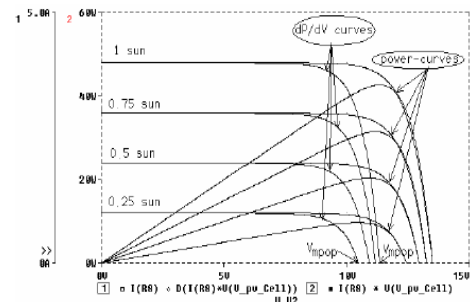


Fig. 7: PV module power-curves and dP/dV curves for varying Insolation.

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.

IX. SHADING

The shading effect is produced, if part of the string of PV cells does not receive full illumination due to shadow or otherwise. The shadowed portion of the string operates in third quadrant with negative voltage (reverse bias) and forward current. An arrangement to produce shading effect in PSpice has been shown in Fig. 8(a).

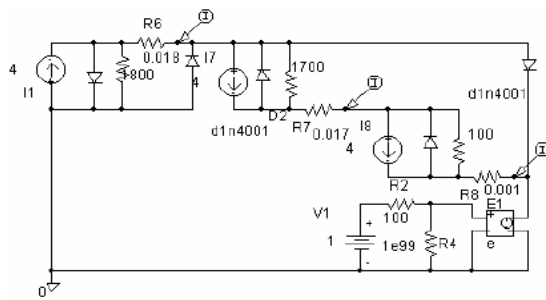


Fig. 8(a): Schematic to simulate Shading Effect.

The illuminated portion of the string operates in fourth quadrant with positive voltage (forward bias) and positive current. The number of shadowed cells will therefore limit the voltage that a shadowed string can produce. The shaded string produces multiple maxima as shown in PSpice simulated results of Fig. 8(b). The shading effect may severely limit the power produced because MPP tracking algorithms may tend to operate PV string on these multiple maximas, and if so happens it will limit the power produced.

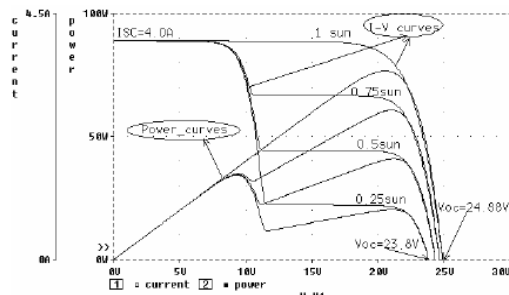


Fig. 8(b): V-I Characteristics & power-curves for PV module under Shading.

X. CONCLUSION

This paper presents PSpice study of PV cells and modules for varying equivalent circuit parameters R_s , R_{sh} and diode model parameters N , I_s and their interdependencies. The V-I characteristics and P-V characteristics are studied for varying solar Insolation and Temperature. An Experimental set up to obtain V-I Characteristics is also discussed. The effect of shading and resultant multiple maxima is also clearly brought out.

APPENDIX

I & V	Cell output current and voltage
I_{ph}	Photon or light generated current
I_s	PN junction saturation current
q	Electronic charge
N	Ideality factor
K	Boltzman's constant
R_s	Series resistance
R_{sh}	Shunt resistance
T	Operating temperature
I_{SCR}	Short circuit current at 25° C and under 1sun.
K_I	Short ckt. current temperature coefficient at I_{SCR}
λ	Solar Insolation in W/m^2 .
T_{nom}	Nominal temperature
E_g	Forbidden gap
FF	Fill Factor
n_p	No. of parallel connected cells
n_s	No. of series connected cells

REFERENCES

- [1] Dzong D. Nguyen, and Brad Lehman, "Modeling and Simulation of PV arrays under changing Illumination conditions," *IEEE COMPEL Workshop Troy, NY, USA*, July 16-19, 2006, pp. 295-299.
- [2] A. Zekry and A. Al-Mazroo, "A Distributed SPICE Model of a Solar Cell," *IEEE Transactions on Electron Devices*, Vol. 43, No. 5, May 1996, pp. 691-700.
- [3] David L. King, James K. Dudley, and William E. Boyson, "A Simulation Program for Photovoltaic Cells, Modules, and Arrays," *25th IEEE PVSC Conf.*, Washington, DC, May 13-17, 1996, pp. 691-696.
- [4] J.A. Gow, and C.D. Manning, "Development of a photovoltaic array model for use in power electronic simulation studies," *IEE Proceeding Electric power Application*, vol. 146, No. 2, March 1999, pp. 193-200.
- [5] Yoshihiro Hishikawa, Yoshihiro Imura, and Toshimitsu Oshiro, "Irradiance-Dependence and Translation of the I-V Characteristics of Crystalline Silicon Solar Cells," *Conference record of 28th IEEE Photovoltaic Specialist Conf.* 15-22 September, 2000, pp. 1464-1467.
- [6] E. Caamafio-Martin, E. Lorenzo, and C. Lastres, "PV Modules Characterization in Rural Electrification Actions," *Conference record of 28th IEEE PVSC*, 15-22 September, 2000, pp. 1472-1475.
- [7] Maria Cotorogea, "Implementation of Mathematical Models of Power Devices for Circuit Simulation in Pspice," *IEEE conf. 1998, VIth workshop on Computers in Power electronics*, 19-22 July, pp. 17-22.
- [8] T.J.McMahon, T.S.Basso, and S.R.Rummel, "Cell Shunt Resistance and Photovoltaic Module Performance," *25th PVSC IEEE conf.* May 13-17, 1996, pp. 1291-1294.
- [9] G. Ioarindis, E. Xanthoulis, and S.N. Manias, "A Novel Uninterruptible Power Supply System with Sinusoidal input-Output Characteristics and simplified Control Circuit," *Proceedings of the IEEE International Symposium on Industrial Electronics*, 1995, Vol-2, pp. 603-609.
- [10] J.F. Hunterand, and J.R. Sites, "Local Photocurrent And Resistivity Measurement With Micron Resolution," *IEEE conf. 2000, Conference record of 28th Photovoltaic specialist conf.* pp. 543-546.

BIOGRAPHIES

R.K. Nema received his Ph.D degree in Electrical Engineering from Barkatullah University, Bhopal, India in 2004. He is currently Assistant 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.

Savita Nema is an Assistant 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.

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.