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

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***Abstract—***
a Pspice simulation based study of photovoltaic's 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.

*Keywords* — Circuit Simulator, Diode model parameters, Insolation, PSpice, PV Cells/modules, Shading

**Nomenclature**

| | |
|---|---|
| I & V | Cell output current and voltage |
| Iph | Photon or light generated current |
| Is | PN junction saturation current |
| q | Electronic charge |
| N | Ideality factor |
| K | Boltzmann's constant |
| Rs | Series resistance |
| Rsh | Shunt resistance |
| T | Operating temperature |
| $I_{SCR}$ | Short circuit current at 25$^o$ C and under 1sun. |
| KI | Short ckt. Current temperature coefficient at $I_{SCR}$ |
| λ | Solar Insolation in W/m2. |
| Tnom | Nominal temperature |
| Eg | Forbidden gap |
| FF | Fill Factor |
| np | N$^o$. of parallel connected cells |
| ns | N$^o$. of series connected cells |

## 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 Photovoltaic's.

## 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].

$$I = I_{PH} - I_S\left(\exp\left(\frac{q.(V+I.R_S)}{N.K.T}\right) - 1\right) - \frac{(V-I.R_S)}{R_{SH}} \quad (1)$$

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.

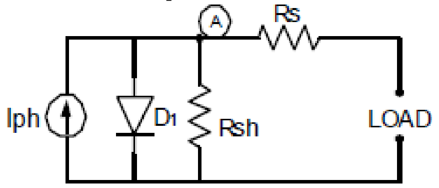


Fig.1: PV Cell circuit model

The complete behavior of PV cells are described by five model parameters (Iph, N, Is, Rs, Rsh) 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 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).

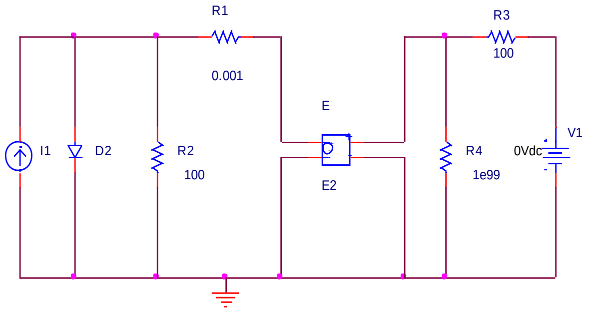


Fig.2(a): Schematic for generating diode curve both under dark and when illuminated.

### *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 $I_{DC}$ as zero. Obviously, the PV cell under Dark is a passive device and behaves like an ordinary diode.

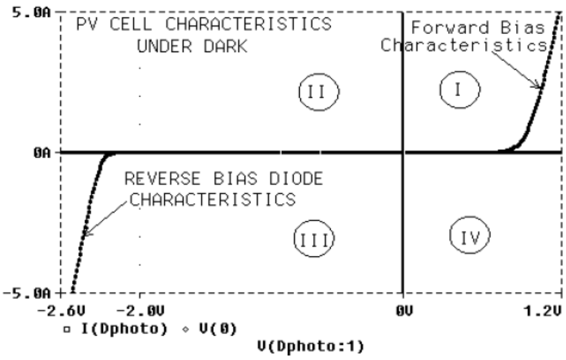


Fig. 2(b): PV Cell Characteristics under Dark

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 I$^{st}$-quadrant and with negative current and negative voltage in III$^{rd}$ –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 Iph 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

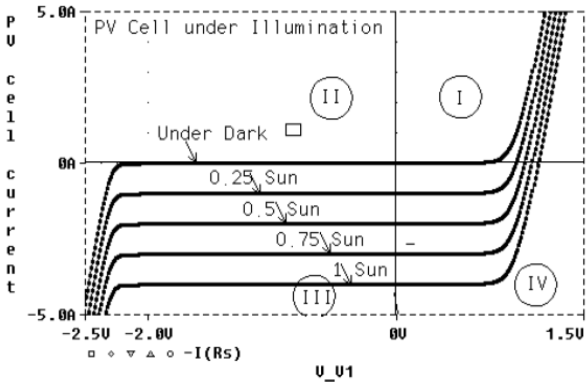


Fig. 2(c): PV cell characteristics under illumination

### *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 IV$^{th}$-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 I$_{st}$ 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.

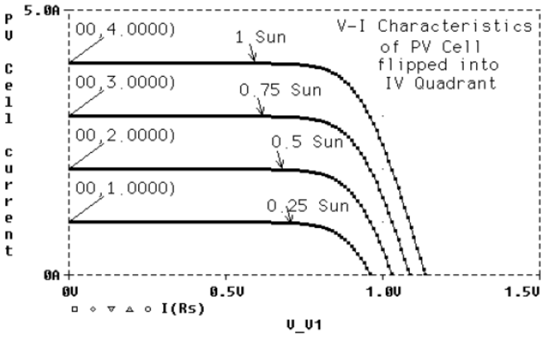


Fig. 2(d): PV Cell Characteristics

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 Diachronic 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 F 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 VR is generated through a 12 bit DAC of Data acquisition card for loading of PV array. By varying VR, 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 VR. 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 Fig. 3(c).

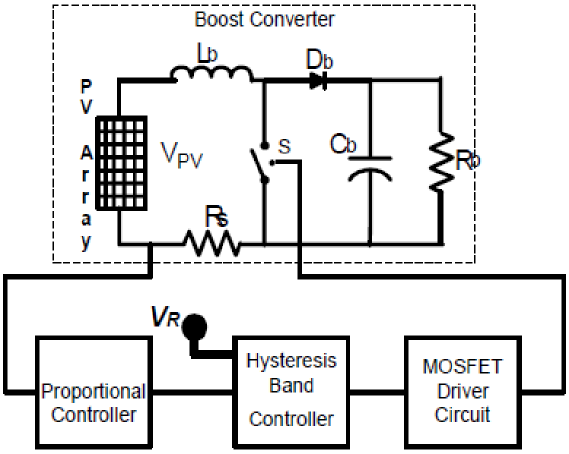


Fig. 3 PV Loading Circuit

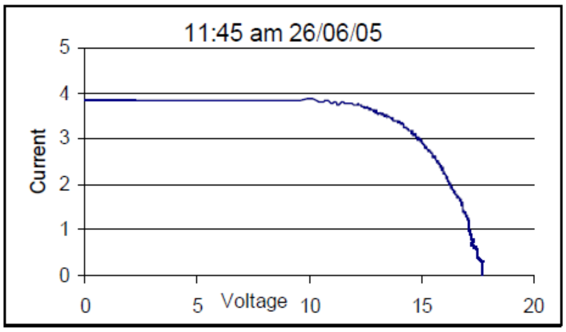


Fig. 3(c): Experimentally obtained V-I Characteristics of PV Module

## IV. MODEL PARAMETER VARIATION

The circuit model of Fig. 1 readily offers an investigation in variation of five model parameter of which two Is & N are related to Diode model, one Iph is related to light or photon generated current and resistance Rs and Rsh 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 (Is & 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.

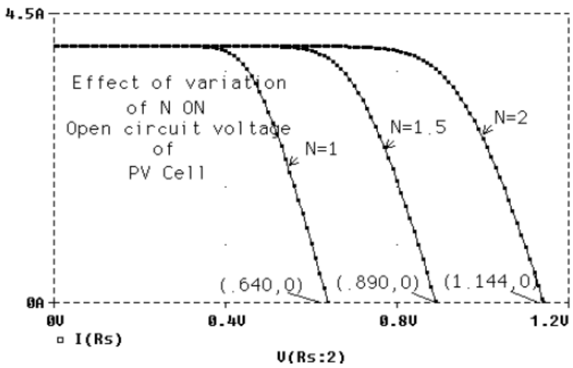


Fig. 4(a): PV Cell Characteristics with varying 'N'

Another important model parameter which reflects variation in V-I characteristics of PV cell is diode reverse saturation current Is. The simulation graph of Fig. 4(b) shows 'V-I characteristics' of PV cell for three different values of Is corresponding to 100nA, 1μA, and 10μA. Obviously the effect of increasing Is 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 Is is now the nested sweep variable.

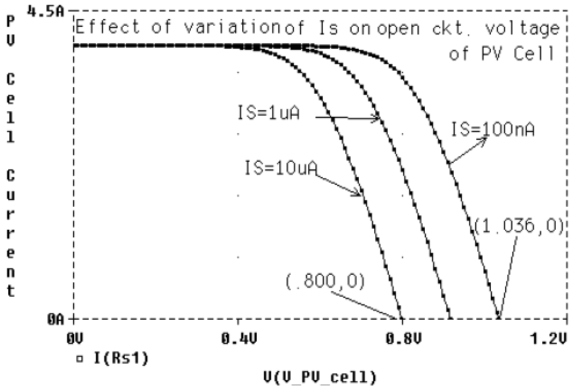


Fig. 4(b): PV Cell Characteristics with varying ‘Is’

A combined effect of varying N & Is on ‘Voc’ is shown in Fig. 4(c), where open circuit voltage ‘Voc’ of PV cell is plotted as a function of N, taking Is as a parameter. The smallest value of Is 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 Is. The above step is now repeated for other values of Is 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.

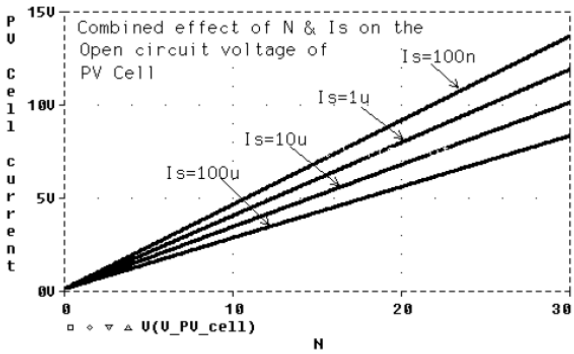


Fig. 4(c): PV Cell Characteristics with varying ‘Is’& N.

*B. Variation in Rs*

The PV cell model of Fig. 1 has two loss representative component Rs and Rsh. The effect of increasing value of Rs 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 Rs. The simulation is produced for three different values of Rs 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 Rs, indicating more output power loss.

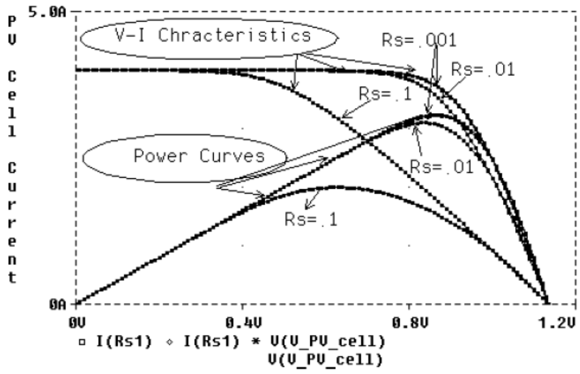


Fig. 4(d): PV Cell Characteristics and power curves for varying Rs.

The power curves demonstrate that higher value of Rs 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):

$$FF = \frac{P_{max}}{V_{OC} I_{SC}} \qquad (2)$$

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

*C. Variation in $R_{sh}$*

The effect of varying Rsh of a PV cell under PSpice can be produced in the same way as is done for varying Rs. The Global parameter is now Rsh in place of Rs. The simulation is produced for three different values of Rsh; 1kΩ, 100Ω & 10Ω. 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 Rsh causes PV cell current to fall more steeply indicating higher power loss and low Fill Factor.

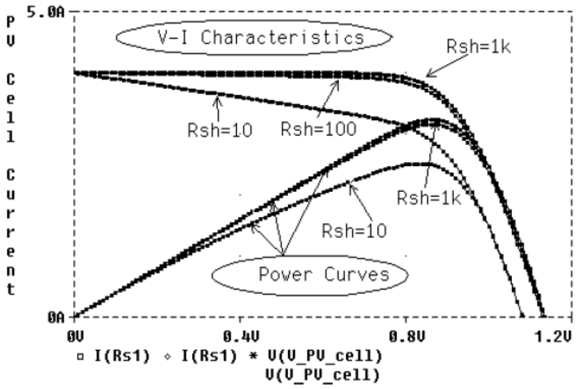


Fig. 4(e): PV Cell Characteristics and power curves for varying Rsh.

All practical PV cell therefore must have high value of Rsh and low value of Rs giving more output power and higher Fill Factor.

## V. 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 Iph is in fact related with solar insolation λ as in (2):

$$I_{PH} = [I_{SCR} + K_I(T - 298)\frac{\lambda}{100} \qquad (3)$$

Where, $K_I = 0.0017$ A/$^o$C,
From equation (3), it can be seen that at constant temperature, the photon generated current 'Iph' is directly proportional to solar insolation. If now the rated 'Isc' of specimen PV cell is 4A under STC (solar insolation of 1 sun at 25$^o$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$^o$C) respectively and can accordingly be set by setting value attribute of current source Iph 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 V1 and nested sweep variable is 'current source' Iph. The simulation is produced for five different values of photon generated current 'Iph' 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).

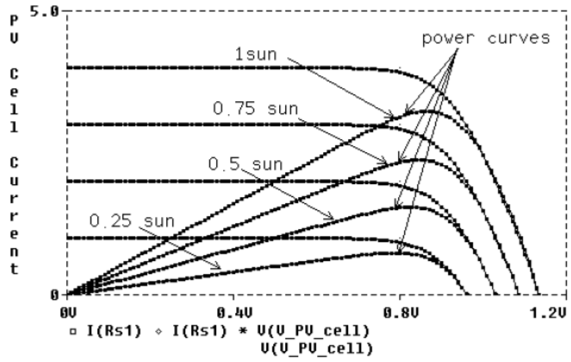


Fig. 5(a): PV Cell Characteristics and power curves for varying Insolation.

From the simulation result it can be observed that as solar radiation falling on PV cell is reduced, both Isc and Voc decreases, but the change in Voc is not as prominent with incident solar radiation as with Isc, 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 'Isc ' 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

$$I_S(T) = I_S[\frac{T}{T_{nom}}]^3 \exp\,[(\frac{T}{T_{nom}} - 1)\frac{E_g}{NV_t}] \qquad (4)$$

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 $V_I$. $T_o$ 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 'Iph' 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).

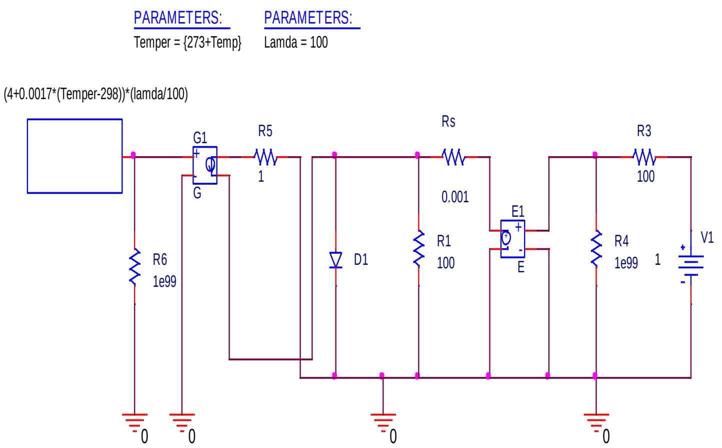


Fig. 5(b): Schematic for PV Cell Characteristics at varying
Temperature.

The simulation result is shown in Fig. 5(c). The Simulator plot the behavior of the PV cell under three different temperatures of 27oC, 57oC and 87oC 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.

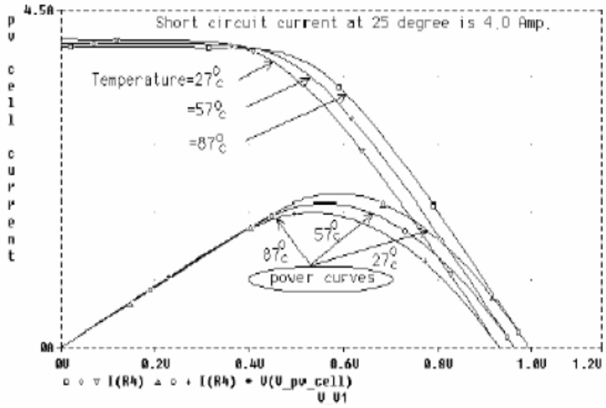


Fig. 5(c): PV Cell Characteristics and power curves for varying Temperature.

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).

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). Uphill 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 Rs & Rsh and is now given as (5).

$$I = n_p I_{ph} - n_p I_s (\exp \frac{q.V}{(N.K.T).n_S} - 1)$$

In a PV module there is only one path available for conduction of current as all the cells are connected in series, therefore np =1. Thus the number of series connected cells ns 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 'Voc' 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 & Is 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 & Is=14.11nA. The plots are very much identical to Fig. 5(a), with the exception that Voc is higher and now represent characteristics for a PV module than for a PV cell.

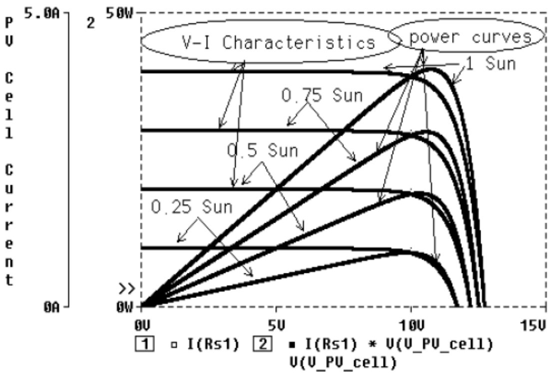


Fig. 6: PV module Characteristics & power-curves for varying Insolation.

## VI. 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.

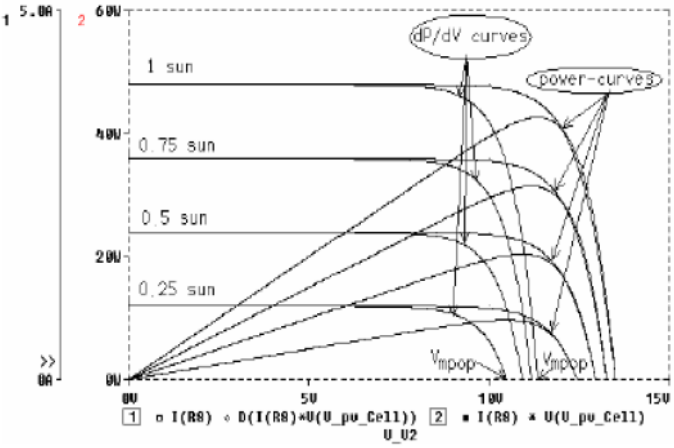


Fig. 7: PV module power-curves and dP/dV curves for varying Insolation.

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.

## VII. 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).

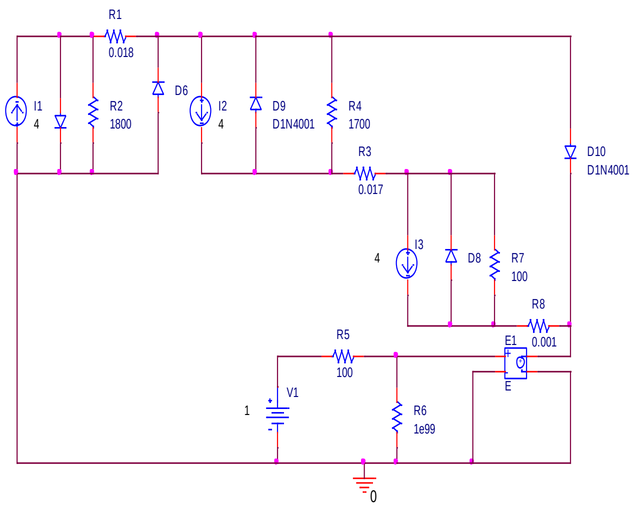


Fig. 8(a): Schematic to simulate Shading Effect.

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 maxima, and if so happens it will limit the power produced.

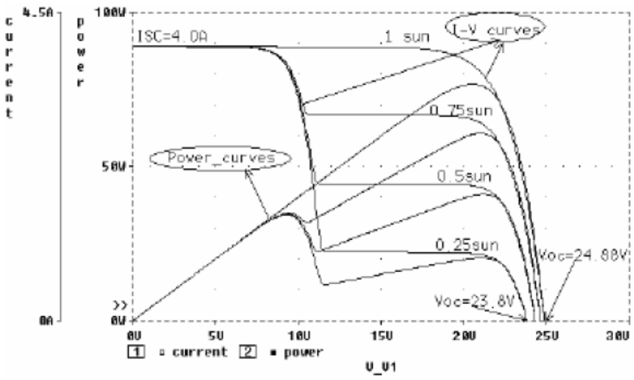


Fig. 8(b): V-I Characteristics & power-curves for PV module under Shading.

## VIII. CONCLUSION

This paper presents PSpice study of PV cells and modules for varying equivalent circuit parameters Rs, Rsh and diode model parameters N, Is 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.

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