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Performance Characteristics of Solar Cells in Spaceunder Shadow Effect

GVS Apoorva*, Dr. T GowriManohar**, Uma BR ***
** (Department of Electrical and Electronics Engineering, SVU College of Engineering, Tirupati.*
*** (Professor, Department of Electrical and Electronics Engineering, SVU College of Engineering, Tirupati.*
**** (Scientist, Solar panel Division, ISRO Satellite Center, Bengaluru.*

ABSTRACT
To study the effect of shadow caused on the solar array in the orbit due to space craft appendages. The shadow due to space craft appendages is a moving shadow with respect to the space craft local time. It is very important to know the effect of shadow on the solar array to estimate power generation. This paper is intended to study the effect of shadow on solar array for different cases theoretically using MATLAB and experimentally.
***Keywords*:** MATLAB, Partial Shading, Simulink, MultijunctionSolar cell

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I. INTRODUCTION

Solar energy is utilized most abundantly for generation of power for both terrestrial and space systems. This solar energy is generated with the help of solar cells. A solar cell produces DC power when light falls on it. A number of solar cells connected together forms solar cell module. Solar cell modules connected together form solar array. A number of solar arrays are connected to obtain the desired values of voltage and current. The solar arrays are positioned in open areas where abundant sun light is available and where the obstructions to the light falling on these solar arrays are minimal.

Solar energy is the most commonly used power source in most of the near earth missions and interplanetary missions. The spacecraft will be provided with a large array of solar panels pointing directly towards the sun. The solar panel consists of array of solar cells each converting sun light into electricity using the photovoltaic mechanism.

The performance of these strings of solar cells is adversely affected if some of the cells are partially shaded. This partial shading may occur because of the shadow of other space objects falling on it or by the shadow of the spacecraft body itself.

A shadow is defined as the absence of solar illumination on a solar cell array due to blocking of the sunlight by a shadow casting object. Shadowing effect is caused by any obstruction which prevents a solar cell or solar panel connected in series from receiving the same incident irradiance level. If some solar cells in a solar panel are receiving a certain amount of irradiation while others receive a lower level of irradiation, the solar cells with a lower level of irradiation will produce less photocurrent.

Shadow effect on terrestrial areas will be mainly caused due to tree branches, leaves, bird droppings, passing clouds, dust, buildings etc. The shadow caused on the satellite solar cells will be due to the satellite body appendages itself.

During darkness, the solar cell is not an active device [2]. It works as a diode, i.e., a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply it generates a current I_d, called diode current or dark current. The diode determines the I-V characteristics of the cell.

A shadow falling on a group of cells will reduce the total output by [3]

(i) Reducing the energy input to the cell.
(ii) Increasing energy losses in the shaded cells.

When a cell is shadowed, it acts as a load i.e. it will takecurrent from other cells, instead of generating on its own. Because of shading of the cell, its short circuit current will be lower than the module current causing the cell to become reverse biased leading to power dissipation. This excessive power dissipation causes an increment in temperature which leads to the creation of the hot-spots which can potentially damage the entire cell. The damage due to shadow can be avoided by connecting a bypass diode across the affected cell. The bypass diode allows an alternative path for the load current.

Parallel connected PV array is dominant under shaded condition. So it is the best possible configuration.

If two cells of unequal output are connected in series the terminal behavior of this cell pair is obtained by summing the cell voltages at constant current values. In a pair of cells, a shadowed cell limits the output from higher output cell number 2. The amount of limiting depends on the reverse characteristics of cell number 1.

MATLAB Simulink provides a platform to calculate the P - V and I - V characteristics of solar cell by continuously varying the load connected to it.

In this paper we discuss about the I-V characteristics of the solar cells of satellites in normal condition and partially shaded conditions. We will study the characteristics of partial shading both practically and by simulation in MATLAB and compare the results.

II. SOLAR CELL

The Equivalent circuit of solar cell [4] consists of a current source in parallel with a diode, a series resistance and a shunt resistance. This equivalent model can be of single diode model, two diode model and three diode model. The basic model commonly used is single diode model. Here we use single diode model to derive the I-V characteristics of solar cell.

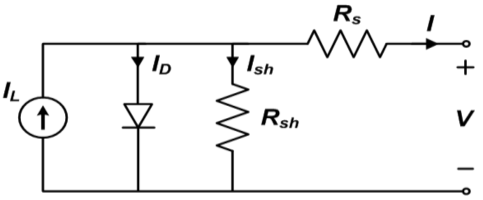

Fig-1: Equivalent circuit of solar cell

From the equivalent circuit, it is clear that the current produced by the solar cell is equal to that produced by the current source minus the current that flows through the diode minus the current that flows through the shunt resistor:

$I = I_L - I_D - I_{SH}$------------------------(1)

where

I = output current (amperes)

I_L = photo generated current (amperes)

I_D = diode current (amperes)

I_{SH} = shunt current (amperes).

The current through these elements is governed by the voltage across them:

$V_j = V + IR_S$---------------------------------- (2)

Where

V_j = voltage across both diode and resistor R_{SH} (volts)

V = voltage across the output terminals (volts)

I = output current (amperes)

R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$I_D = I_0\{\exp\left(\frac{qV_j}{nkT}\right) - 1\}$---------------------------- (3)

where

I_0 = reverse saturation current (amperes)

n = diode ideality factor (1 for an ideal diode)

q = elementary charge

k = Boltzmann's constant

T = absolute temperature

At 25°C, kT/q=0.0259 volts.

By Ohm's law, the current diverted through the shunt resistor is:

$I_{SH} = V_j / R_{SH}$-------------------------------------- (4)

where

R_{SH} = shunt resistance (Ω).

Substituting the above in first equation, the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltageis given below:

$I = [I_L - I_o\left(\exp\left[q\left(\frac{V+IR_S}{nkT}\right)\right] - 1\right) - \frac{(V+I\,R_S)}{R_{SH}}]$-- (5)

Solar cells exhibit nonlinear I-V and P-V characteristics with irradiation and temperature. The typical I-V and P-V characteristics of solar cell are shown in figures below:

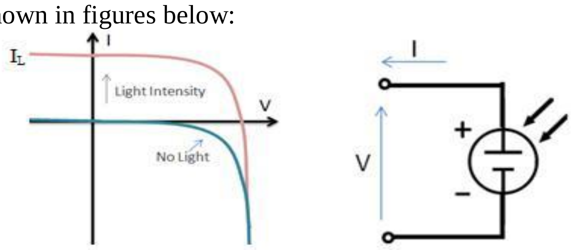

Fig-2

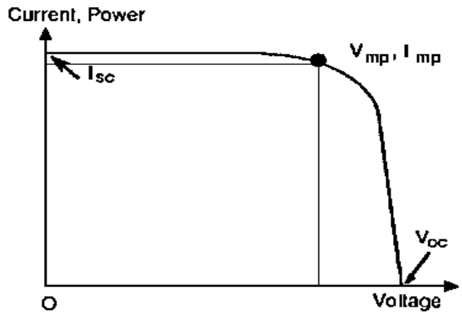

Fig-3: I-V curve of solar cell

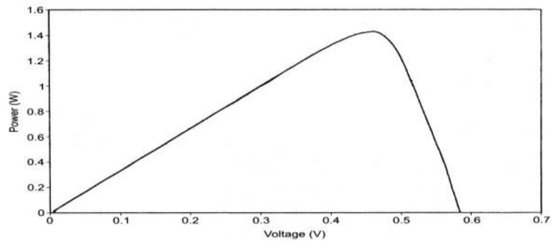

Fig-4: P-V curve of solar cell

The parameters required for the generation of I-V and P-V curves are[5]

- Short circuit current (I_{sc})
- Open circuit voltage (V_{oc})
- Maximum power (P_{max})
- Voltage at Pmax (V_m)
- Current at Pmax (I_m)

III. MATLAB IMPLMENTATION / EXPERIMENTION:

The objective of the present study is to observe the performance characteristics of Solar cells used in Space subjected to partial shadow conditions. To achieve this, MATLAB programming and Simulink Model have been generated. Using these, I-V characteristic curves are generated. Experimental analysis has also been conducted to validate the results obtained from programming and modeling.

In this study, a solar array consisting of 25 solar cells in series has been considered. These are multi junction Solar cells, connected in series. Each cell has a bypass diode connected across it. The typical parameters of the solar cells are shown in table 1:

Table – 1

I_{sc} (amp)	0.5175 A
I_{mp} (amp)	0.4804 A
V_{mp} (volts)	2.2424 V
V_{oc} (volts)	2.5512 V

All the solar cells are considered to be equally illuminated. As these are only series connected cells the output current will be constant for all the cells and the voltage will be increased/ added. The overall panel open circuit voltage will be ~ 63.78 V(25x2.5512).

MATLAB CODING

The MATLAB coding has been preparedfor I-V characteristics of the solar cell. The algorithm for generation of I – V curves using MATLAB code is as follows:

Step 1: Input all the required data such as short circuit current (I_{sc}), open circuit voltage (V_{oc}), voltage atP_{max}, current at P_{max}, number of cells connected in series and parallel.

Step 2: Input the number of shadowed cells and percentage of shadow on those cells.

Step 3: Calculate all the values required using the equations of solar cell given in the previous sections.

Step 4: Voltage isincreased from zero to open circuit voltage with an increment of 0.001 volts is taken to calculate output voltages and output currents.

Step 5: Calculate output currents and output voltages for partially shaded cells.

Step 6: Plot I-V curves corresponding to the output values obtained.

SIMULINK MODEL

There are different ways of connecting the blocks in the Simulink for the modeling of solar cells. We can connect the blocks by taking the equations given in the above sections or by directly taking the solar cell parameter [6] from the Simulink library.

To model the Simulink using solar cell we should give open circuit voltage (V_{oc}) and short circuit current (I_{sc}) of the solar cell in the parameters. The solar cell block consists of three terminals. One terminal is to input the irradiation and other two terminals are positive and negative terminals of the solar cell. The solar cell block from the Simulink library is shown in the following figure:

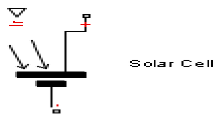

Fig-5: Solar cell

In order to simulate the effect of shading, we simulate the solar string constructed out of 25 cells connected in series arrangement. This arrangement can be extended to any number of solar cells depending on our requirement.

Step 1: Connect the required number of solar cells in series by connecting the negative terminal of one cell to the positive terminal of other cell.

Step 2: Assign the values of V_{oc} and I_{sc} to the solar cells. Connect the irradiation block to the irradiation terminal of the solar cell.

Step 3: Connect a variable load to the solar cells. Now connect the scopes to the terminals to get I-V characteristics of these cells under full radiation and also under different shading conditions.

The simulink diagram for the I-V characteristics of solar cells is shown in the figure below:

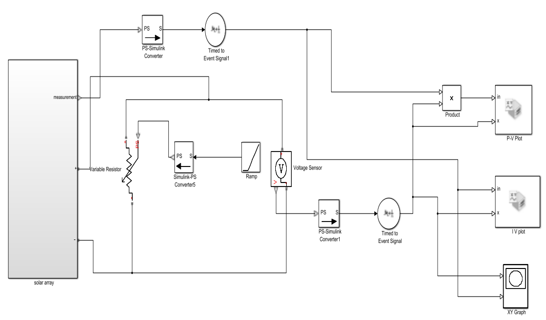

Fig-6: Simulink model

In experimental setup at ISRO Satellite Center, Bengaluru, Large Area Pulse Solar Simulator (LAPSS) is used to give a light pulse for 2 seconds to illuminate the cells. The solar cells were with opaque paper for different percentage shadings.

Case-1: Without shadow

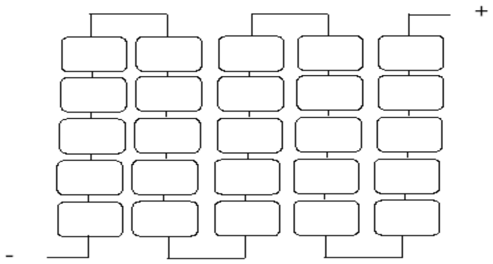

Fig -7: Without Shadow

In this case all the solar cells are equally illuminated without any shadow on them. As there are only series connected cells, the output current will be constant for all the cells and the voltage will be increased. The overall panel voltage is (25x2.5512) 63.78 V. The experiment is done by illuminating the solar cells with the help of LAPSS. This LAPSS will produce a light pulse for 2 seconds. This experiment is conducted at 25°C ambient temperature. The I - V characteristics of solar cell are shown below:

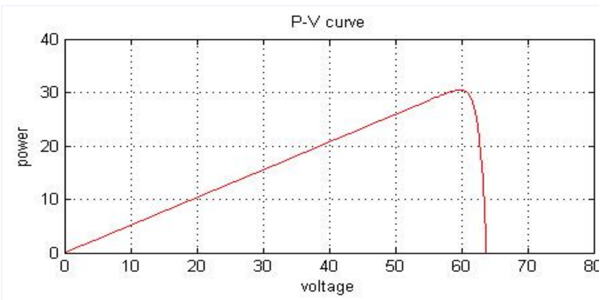

Fig-8: Solar cell P-V curve

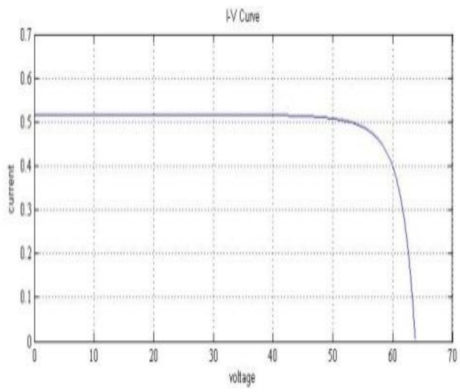

Fig-9: I-V curve without shadow from MATLAB

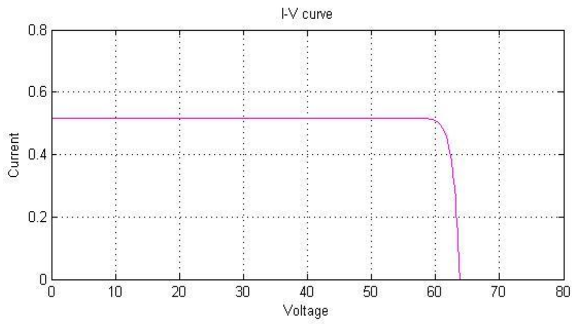

Fig-10: I-V curve without shadow from simulink

The above curves show that the current of 0.5175 A and the output voltage is 63.78 V. As there is no shadow effect, the full voltage and full current output is received.

The I – V curve from the experiment is shown below:

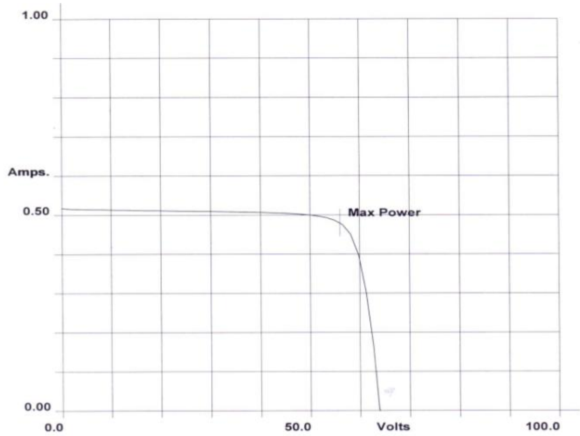

Fig- 11: I-V curve without shadow from Experiment

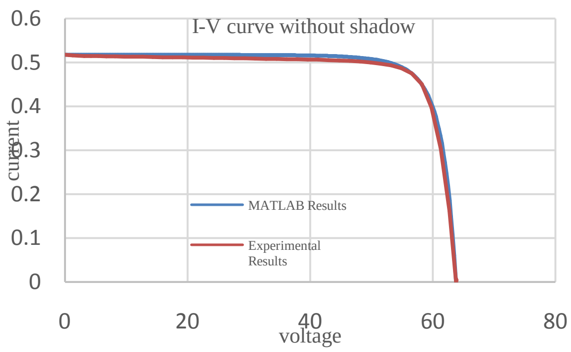

Fig-12 : Comparison between MATLAB & experimental I-V curves without shadow

Case-2: 3 Cells – 50% Shadow

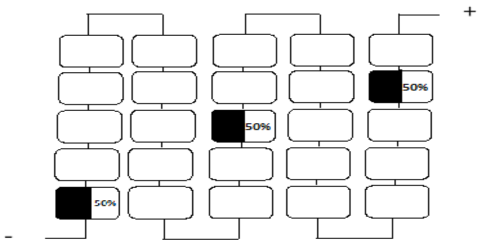

Fig-13: 3 Cells – 50% Shadow

In this case, three cells are 50% shadowed. As these cells are 50% shadowed, there will be reduction in production of power and current, but overall voltage of the panel remains unchanged.

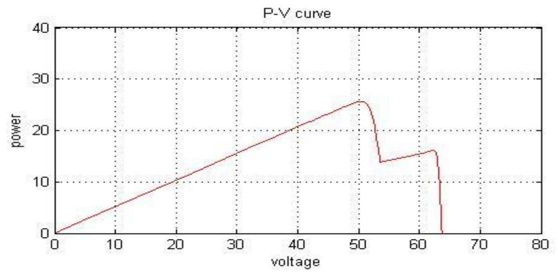

Fig-14: P-V curve for 3 cells 50% shadow

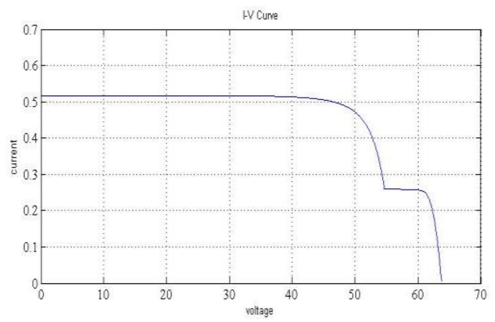

Fig-15: I-V curve for 3 cells 50% shadowed

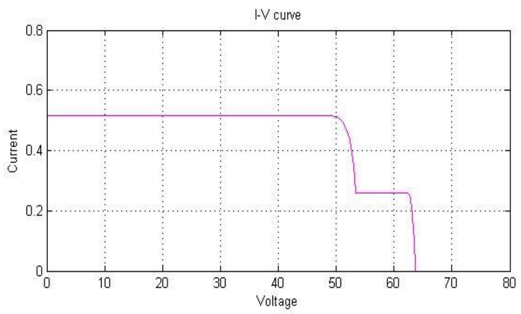

Fig-16: I-V curve for 3 cells 50% shadowed from Simulink

In the above figures, we can see that there is a kink in the curve. The fully illuminated cells produce full current and voltage. The shadowed cells produce reduced current. The initial horizontal line signifies the working of fully illuminated cells. The kink signifies that there is a reduction of current production in the panel by the partially shadowed cells. The voltage of fully illuminated cells and partially shadowed cells put together will be the overall output voltage. This behavior is expected because of the bypass diode presented in each individual cell. Otherwise the shadowed cell would have become reverse biased and the no string output was expected.

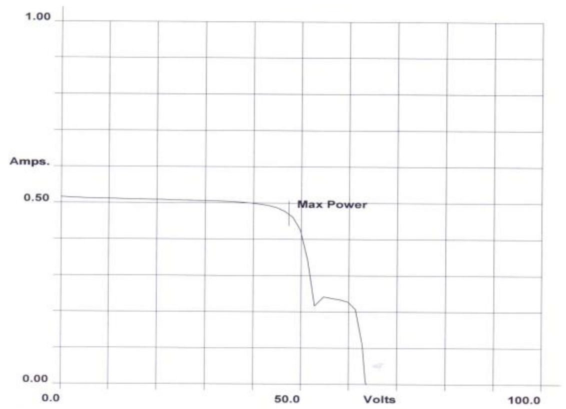

Fig-17: I-V curve for 3 cells 50% shadowed from Experiment

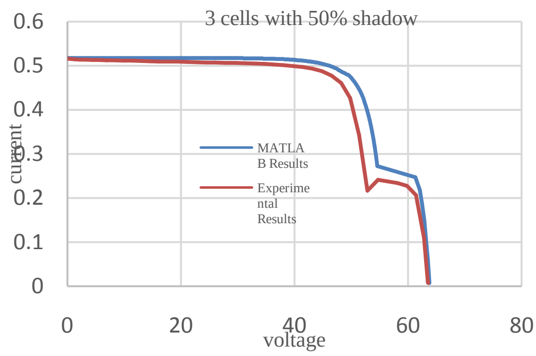

Fig-18: Comparison between MATLAB & experimental I-V curves for 3 cells 50% shadowed

Case-3: 2 Cells – 50% & 1 Cell – 25% shadow

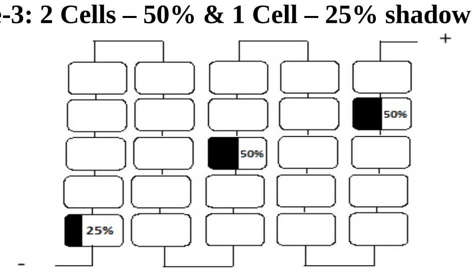

Fig-19: 2 Cells – 50% & 1 Cell – 25% shadow

In this case, two cells are 50% shadowed and one cell is 25% shadowed. The shadowed cells produce reduced amount of current only.

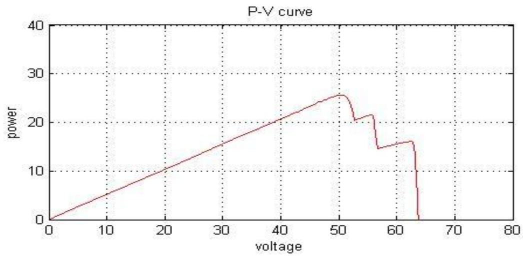

Fig-20: P-V curve for 2 cells 50% and 1 cell 25% shadow

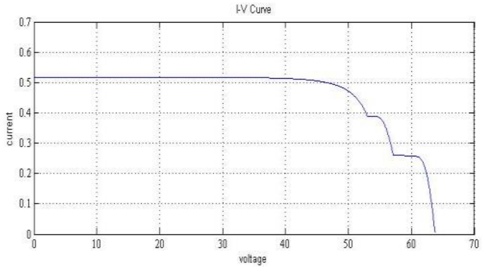

Fig-21: I-V curve for 2 cells 50% shadowed & 1 cell 25% shadowed

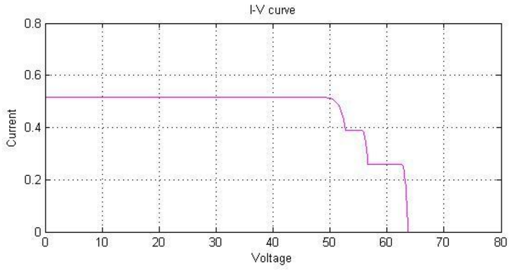

Fig-22: I-V curve for 2 cells 50% shadowed & 1 cell 25% shadowed from Simulink

In the above figures, we see that there are two kinks in the curve. The initial horizontal line of the curve signifies the working of the fully illuminated 22 cells. The first kink, signifies the 25% shadowed cell and the second kink signifies the 50% shadowed cells. The overall performance of the circuit can be accessed from the curve.

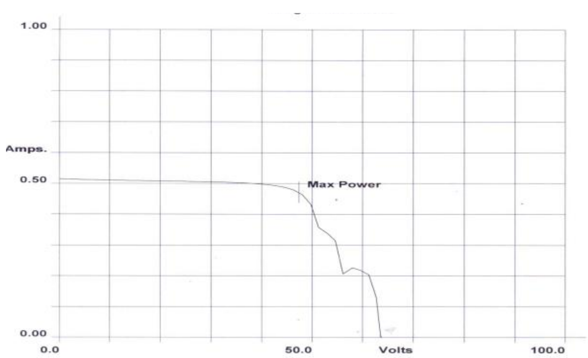

Fig-23: I-V curve for 2 cells 50% shadowed & 1 cell 25% shadowed from Experiment

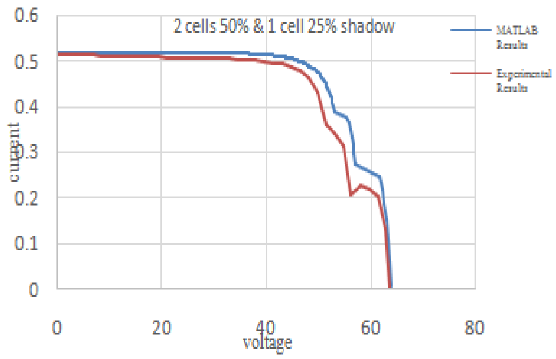

Fig-24: Comparison of matlab& experimental I-V curves for 2 cells 50% shadowed & 1 cell 25% shadowed

IV. RESULTS

1. Due to partial shading, output power of the panel decreases.
2. The output current of the cell decreases according to the shading percentage of the cell.
3. As there are multiple shaded cells with different percentage shadows there will be multiple kinks in the I-V curve.
4. The number of kinks depends on the number of different percentage shadings of cells.
5. In all the cases the bypass diode present in each cell helps in avoiding the reverse bias and helps in producing partial power output.
6. If any cell is fully shaded, the output current of that particular cell becomes zero and hence that cell will be bypassed due to the incorporation of bypass diode, resulting in reduction in output voltage of the panel, to the effect of those many fully shaded cells.

V. CONCLUSION

I -V Characteristics of PV panel are studied in this paper. The effects of shadows on PV panel with different shadow percentages at different locations are carried out. MATLAB / SIMULINK software has been developed with different shading percentages for different number of cells and the effects of those shadows on panel are obtained. MATLAB coding is also done to get I-V characteristics of Solar cells for different shading conditions. Experimental analysis has been carried out using 25 cells, connected in series. All the values obtained from MATLAB coding and MATLAB Simulation model are validated with experimental values. This experiment is useful to know the shadow effect on solar panels under various conditions.

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