Engineering Thesis Project: ENG460

Development of a Photovoltaic Array Simulation Tool for Shading and Mismatch Evaluation

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Declaration

I declare that this thesis is my own account of my research and contains as its main content work which has not previously been submitted for a degree at any tertiary institution.

....

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23/11/2009

ENG460 Engineering Thesis

Academic Supervisor endorsement pro forma

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I am satisfied with the progress of this thesis project and that the attached report is an accurate reflection of the work undertaken.

Signed:

Date:

Abstract:

This dissertation explores the development of a simulation model in ICAP to illustrate the effects of shading and mismatch of photovoltaic cells within a photovoltaic array. The intention of designing the simulation model was to build a simulation tool which could be utilised as a teaching resource for illustrating the effects of shading and mismatch of photovoltaic arrays for renewable energy engineering education. The process of building such a model initially involved building a single cell in ICAP which was based on a single diode model to illustrate the current and voltage output of a single cell. Once the output resembled the output for an ideal I-V curve, the next step was to build several cells in series with the inclusion of two bypass diodes in parallel with a series connection of 18 solar cells per bypass diode.

To simulate unshaded conditions, the photo-generated current of each solar cell was the same and the output subsequently resembled the same output as that for an ideal I-V curve. Shaded conditions were simulated by reducing one of the solar cell photo-generated currents by half the original current value. The resulting output had an unchanged short circuit current and open circuit voltage. However, the overall I-V curve had a changed I-V curve characteristic, as well as a reduced power output.

Once a module of 36 cells with two bypass diodes was constructed in ICAP, testing was conducted in the Spi-Sun Simulator 460 at the Remote Outdoor Testing Area (ROTA) compound to simulate the outputs for a mono-crystalline module with and without bypass diode connections as well as for unshaded and shaded conditions. The current and voltage results from the simulation were then converted to a Microsoft Excel file. Curve fitting was performed to obtain modified parameters to input back into the module model in ICAP. The modified parameters were then input back into the model in ICAP to illustrate the I-V curve outputs for a module with and without bypass diode connections as well as for unshaded and shaded conditions.

The outputs from the ICAP simulation were then exported from the ICAP graph into a text delimited file which was then converted into a Microsoft Excel file. The ICAP results were compared with the ROTA results and whilst the short circuit current and open circuit voltage values were the same, there was some discrepancy with the curve fitting.

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Introduction

This project focuses on the development of a simulation model that illustrates the effects of shading and mismatch of photovoltaic cells within a PV array. The simulation model is based on a single-diode model. The simulation model was designed with the ICAP software. The purpose of this development was to build a simulation tool which could be utilised as a teaching resource for illustrating the effects of shading and mismatch of photovoltaic arrays for renewable energy engineering education. The choice of the model will be explained in further detail in chapter 1 and the choice of software will be explained in further detail in chapter 2.

The purpose of the project is developing a simulation tool that can be used for renewable energy engineering education to illustrate the concepts of what happens to the output of a PV module when there is shading and mismatch of photovoltaic cells, with and without bypass diode connections. Once an appropriate model has been developed, the validity of this model will be assessed by comparing the outputs from the developed model to recordings from module shading tests in the Spi-Sun simulator 460. The type of module that will be used for testing will be a mono-crystalline module with a configuration of 36 cells and two bypass diodes in parallel with the 36 cells. The method of testing will be explained in further depth in chapter 3.

Once the PV measurements have been obtained from the Sun Simulator, these will be converted into Microsoft Excel to perform some curve fitting to obtain the modified parameters to input into the simulation model. The curve fitting method used is using a single diode equation to obtain the calculated cell current value and use the least errors squared method. This will be explained in further detail in Chapter 5.

Once the modified parameters are input into the model, the outputs of the simulation model will be compared to that of the sun simulator. The comparison of these outputs will be explained in further detail in chapter 7. Once the module output in the simulation program duplicates that of the sun simulator output, then the next step is to build multiple modules to create a photovoltaic array.

Chapter 1 – Background and Literature Review

1.1 - Background:

As Photovoltaic (PV) cells have developed into an established technology, they have also become a more viable option to provide and supplement power for a wide range of applications. However, two of the problems that still affect the performance and reliability of photovoltaic modules are shading and mismatch. Shading occurs when PV systems have been installed in locations where some exposure to shading is inevitable such as in circumstances where there is not enough land available to build a PV installation to prevent all types of shading.

Shading of PV cells may also occur in situations such as leaves, bird droppings or dirt falling on PV cells as well as by surrounding structures (building and trees) and by shadows casting over the PV cells. The problem with shading is that it can significantly reduce the power output of a PV array. In extreme cases almost the entire array output can be lost as a result of shading of a single cell. A situation of mismatch may occur due to shading as well because cells with different performance characteristics are combined in an array.

Mismatch occurs when photovoltaic cells that are connected to form an array do not have matching characteristics. The condition of mismatch will result in power loss. When the characteristics of cells within a PV array differ, individual cells may not be operating at their optimal level and this causes a reduction in array output power. (1) Bypass diodes are commonly used in PV arrays to protect against the effects of shading by limiting the effects of power loss and hot-spot power dissipation. (5)

"A bypass diode is connected in parallel, but with opposite polarity, to a solar cell. Under normal operation, each solar cell will be forward biased and therefore the bypass diode will be reverse biased and will effectively be an open circuit." (4).

The figures below will be used to explain the effects of shading and mismatch of one cell within a series connection of ten cells and will also assist in explaining the effects of bypass diode connection in a series of cells.

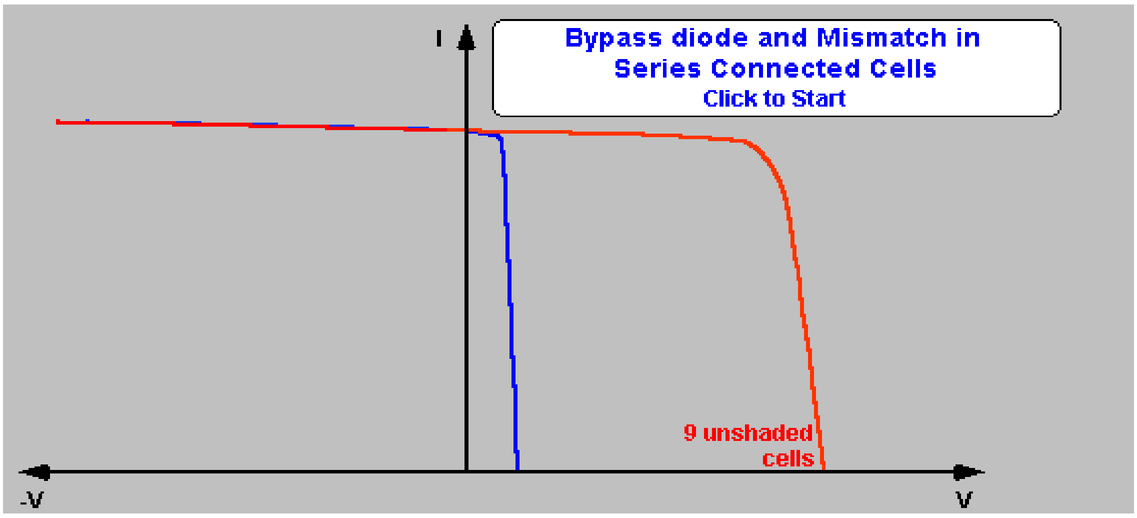


Figure 1 - Preventing hot-spot heating with a bypass diode. For clarity, the example uses a total of 10 cells with 9 unshaded and 1 shaded. A typical module contains 36 cells and the effects of current mismatch are even worse without the bypass diode, but are less important with the bypass diode. (4)

In Figure 1 the red I-V curve represents 9 unshaded cells and the blue I-V curve will represent 1 unshaded cell.

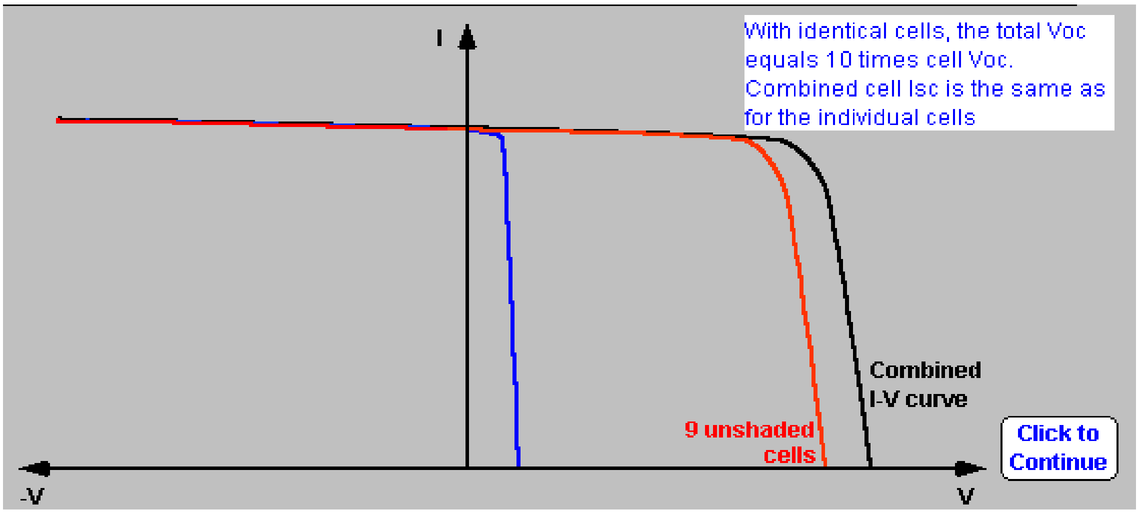


Figure 2 - Combined I-V Curve Output (4)

In Figure 2 the black curve represents the combined I-V curve. At the moment both the blue I-V curve and red I-V curve are modelling unshaded conditions. Because they both have identical cell properties the total open circuit voltage is ten times that of the individual cell voltage. However, the combined cell short circuit current is the same as that for the individual cells. The next figure will illustrate the effects of shading on a cell.

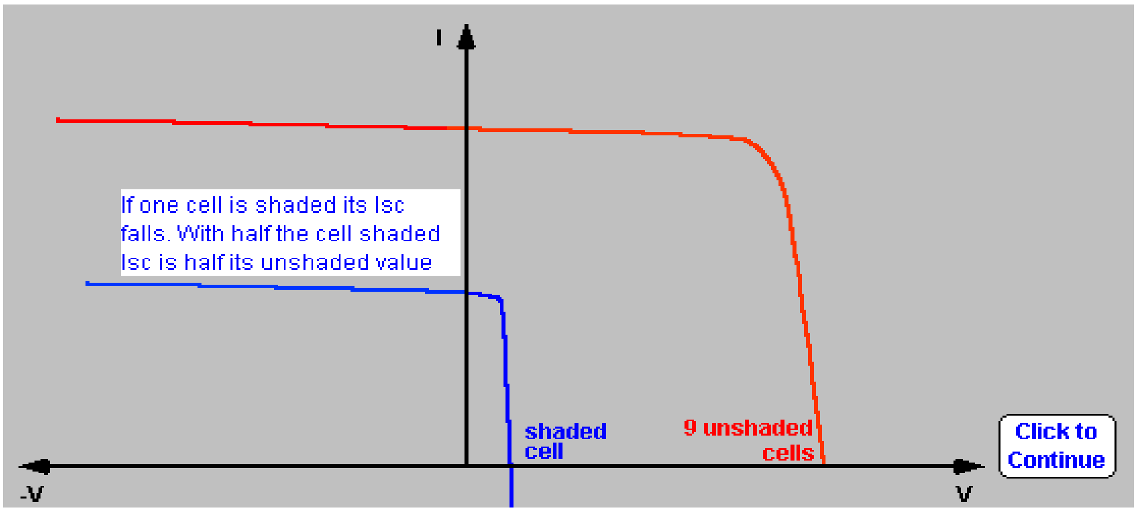


Figure 3 - The Result of One Cell Shaded (4)

As can be observed in Figure 3 if one cell is shaded, its short circuit current will fall. So if one cell is half shaded its short circuit current will fall to half of that of the short circuit current value for the unshaded cell.

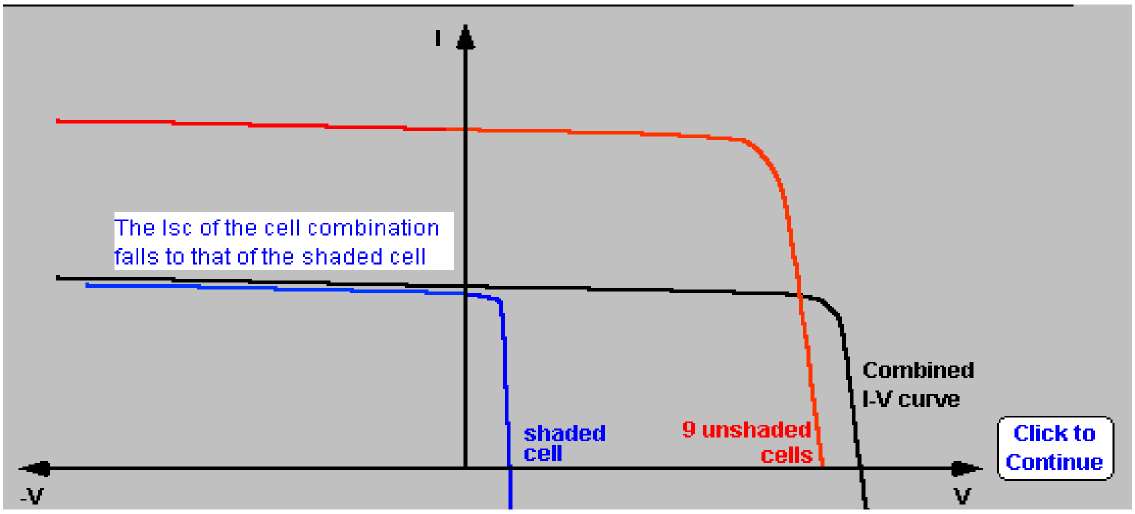


Figure 4 - Combined I-V curve of One Shaded Cell in an Assembly of Ten Cells (4)

The result of the combined I-V curve output is that the shading of a cell has created a load which can be seen in the combined I-V curve output across the remaining unshaded cells. As a result the short circuit current of the cell combination output falls to that of the shaded cell short circuit current output.

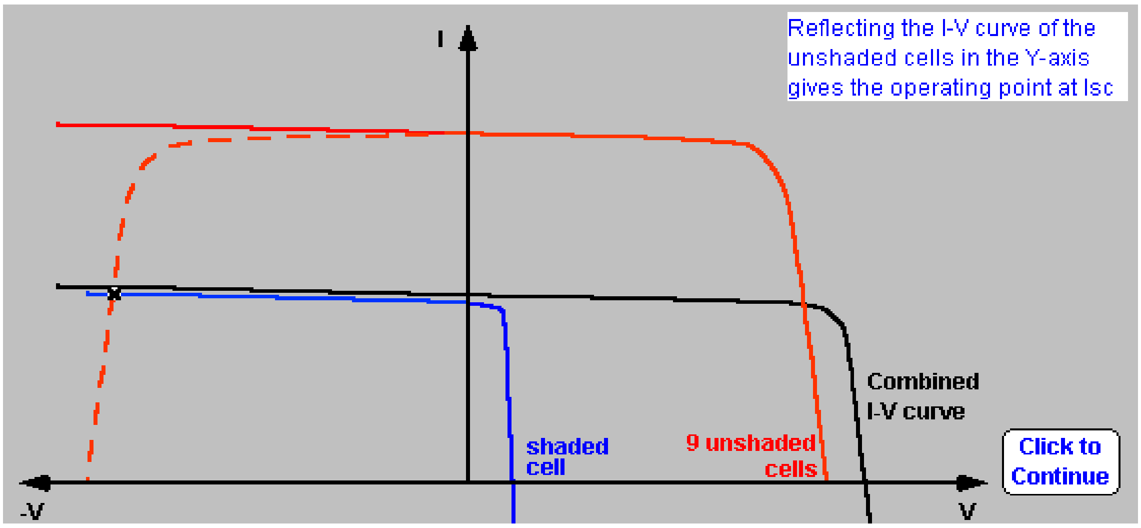


Figure 5 - Reflecting the I-V Curve of the Unshaded Cells (4)

Reflecting the I-V curve of the unshaded cells in the Y-axis gives the operating point at short circuit current.

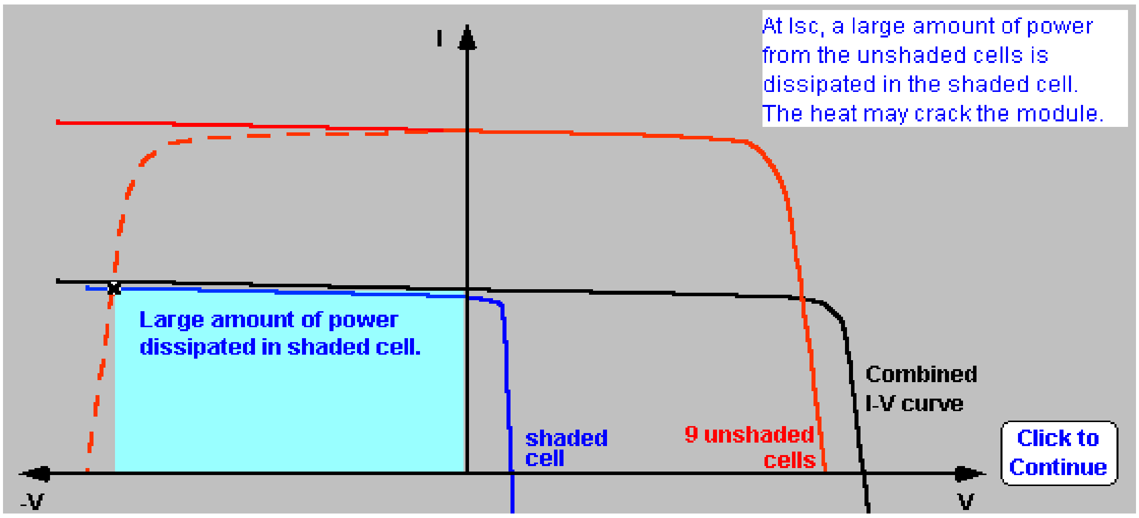


Figure 6 - Resulting Power Dissipation from Unshaded Cells (4)

Due to the reduction of the short circuit current output of the combined I-V curve, a large amount of power from the unshaded cells is dissipated in the shaded cell. This dissipation of power can cause hot spots to appear on a module. The resulting dissipated heat may consequently crack the glass casing of the module. The next figure will illustrate the effects of adding a bypass diode connection in parallel with the shaded cell.

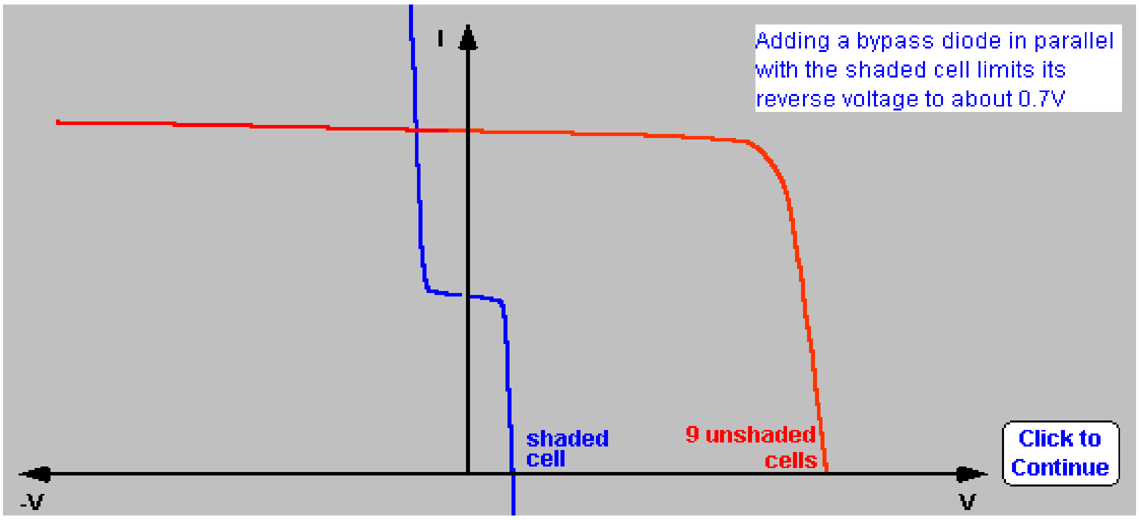


Figure 7 - Adding a Bypass Diode Connection in Parallel with the Shaded Cell (4)

Figure 7 illustrates the effects of adding a bypass diode connection in parallel with the shaded cell. The connection of the bypass diode limits the reverse bias voltage of the shaded cell to the voltage drop across the cell. According to Figure 7 it is approximately a voltage drop limit of 0.7V.

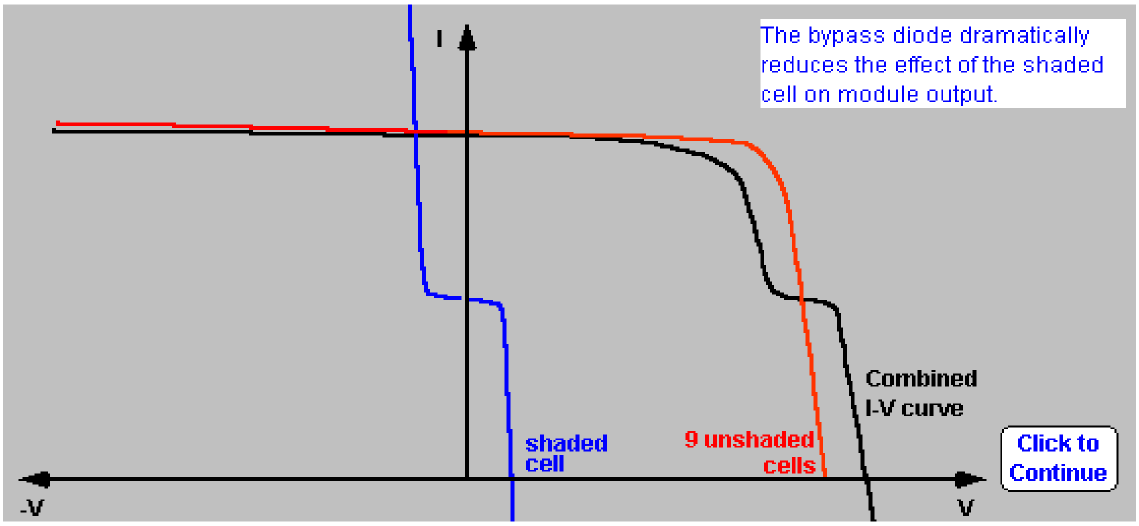


Figure 8 - The Effects of the bypass diode on the output of an assembly of cells (4)

In Figure 8 it is observed that the bypass diode reduces the effect of the shaded cell on the module output. The short circuit current output is the same in Figure 8 as for Figure 2 with the combined output of the unshaded condition. However, there is a dip in the I-V curve output and this corresponds to the effects of the shading of a single cell. The current output at this point drops to approximately half the short circuit current.

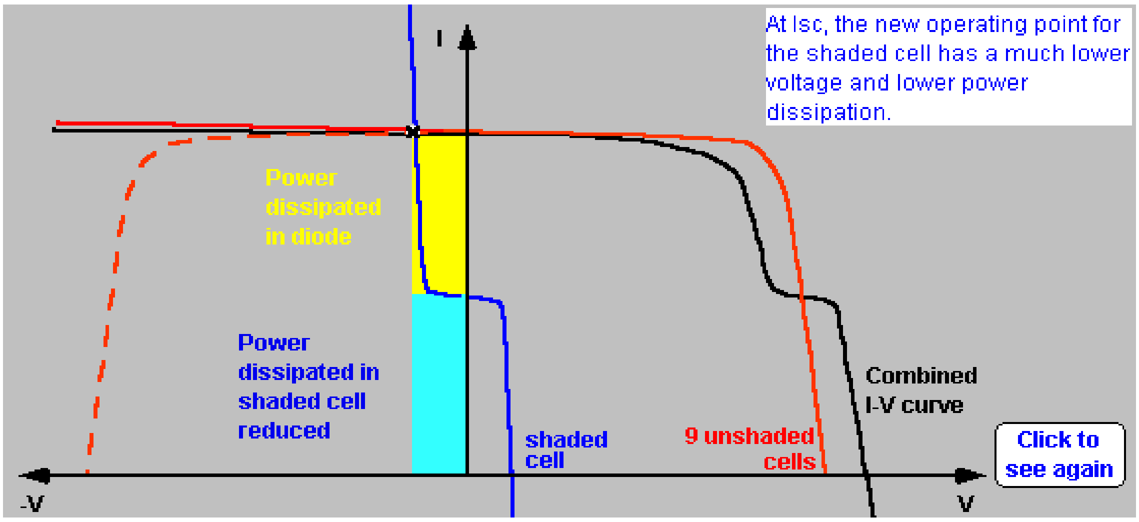


Figure 9 - The effect of power dissipation on an Assembly of Cells with bypass diode connection (4)

In Figure 9 the effect of the power dissipation is significantly lower for the assembly of cells with bypass diode connection than the assembly of cells without bypass diode connection.

Shading and mismatch on photovoltaic arrays is a problem because it reduces the optimal output of the PV array and changes the ideal I-V curve characteristic. The problems of shading and mismatch have been acknowledged and documented for a number of years and there have been numerous proposals for overcoming it. These proposals include the inclusion of bypass diodes within the circuits, series/paralleled circuit design strategies, reduced cell shunt resistance and integral bypass diodes. However, this project will solely focus on illustrating the concepts of shading and mismatch by comparing modules with and without bypass diodes via simulation modelling.

1.2 Single- Diode Model and Two-Diode Model

Models in a range of simulation programs have been developed to illustrate the effects of shading and mismatch on photovoltaic arrays as well as PV performance characteristics. For example, in the thesis titled Tool for Automated Simulation of Solar Arrays Using General-Purpose Simulators (6) the authors have used the PSpice program to model a single-diode representation of the PV array. Whilst under illumination a PV solar cell may be represented by an equivalent circuit. (12) Below in Figure 10 is an equivalent circuit of the single diode model.

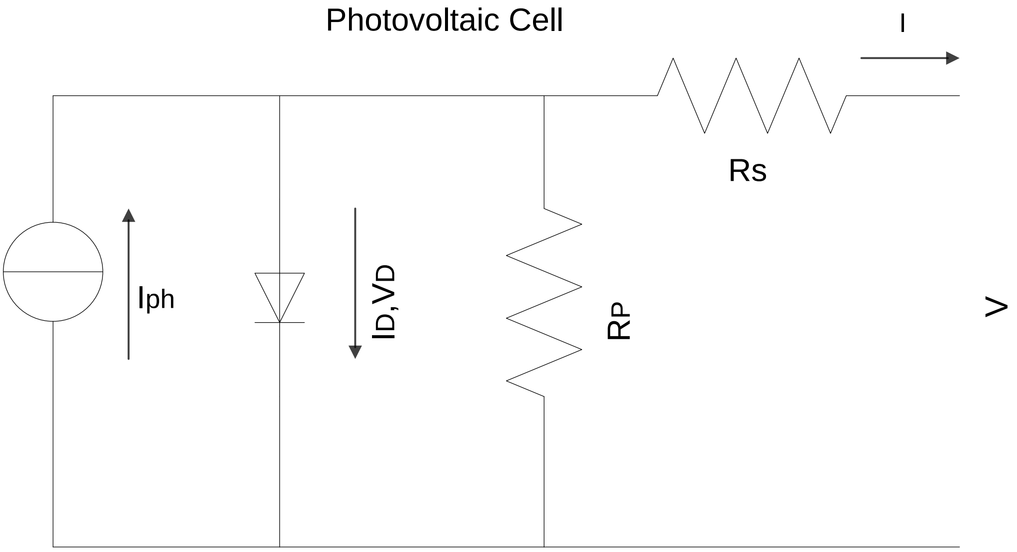


Figure 10 - Single-Diode Model Circuit (2)

$$I = I_{ph} - I_D - I_{RP}$$

$$I = I_{ph} - I_O\left(e^{q\frac{(V+IR_s)}{nKT}} - 1\right) - \frac{(V+IR_s)}{R_P} \quad (2)$$

The equation of the single-diode model is the solar cell characteristic curve equation for the load current in the circuit. Below describes each parameter of this equation.

Parameters:

I = Cell Current

Iph = Photo-generated Current

Io = Saturation Current

V = Cell Voltage

Rs =Series Resistance

RP = Parallel or shunt resistance

q = Unit Charge

n = Ideality factor

k = Boltzmann’s Constant

T = Cell Temperature

PVSim is another example of a program which has been created with the purpose of illustrating the effects of shading and mismatch. PVSim is a Microsoft based program and this program has been created to analyse individual cells, to analyse the effects of cell mismatch or reverse bias (“hot spot”) heating in modules, and to analyse the performance of large arrays. (7) According to the authors of the PVSim publication, the PVSim is most appropriate for cells that can be modelled using a two-diode equivalent circuit. Below in Figure 11 is the equivalent two-diode model circuit.

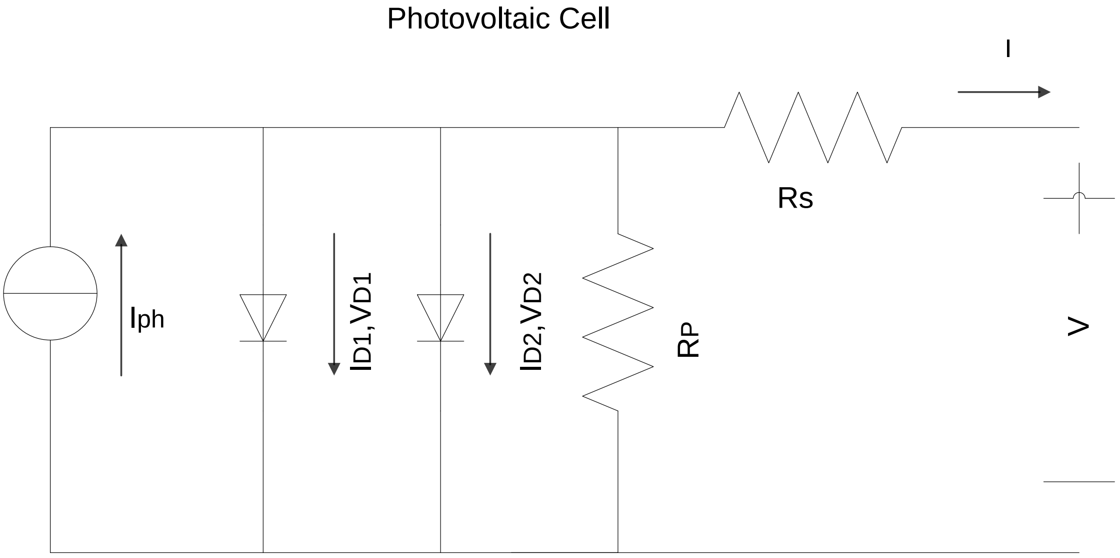


Figure 11 - Two-Diode Model Circuit (4)

$$I = I_{ph} - I_{o1}(e^{\frac{(V+IR_s)}{VT_1}-1}) - I_{o2}(e^{\frac{(V+IR_s)}{VT_2}-1}) - \frac{(V+IR_s)}{R_P} (2)$$

1.3 - Development of Programs with the Capability of modelling the effects of Shading and Mismatch of Photovoltaic Cells

Several programs have been developed with the capability of illustrating the effects of shading and mismatch. These programs which have the capabilities to model either single-diode or two-diode models include:

- PVSim
- Simulink
- SPICE
- Programs which the user estimates the shading losses (such as SOLDIM and GOMBIS).
- Programs where the horizontal shading can be entered graphically (such as PVS, Greenius and SolEm).
- Programs that allow three dimensional shading analyses (such as PVSYST, Pvcad, 3D solarWelt and Solar Pro).

A scientific study on the problem of shading was conducted at the Technical University Berlin by Siegfriedt (2) using the SPICE simulation program. The SPICE program was used to determine the PV array characteristic I-V curves and the expected power losses depending on different shading scenarios. This investigation found that when the array was connected in series that the characteristic curves were independent to the position of the shaded modules, whereas the parallel-connected PV array produced different characteristic curves for different shading situations.

I have chosen to base my simulation on the single-diode model as opposed to the two-diode model. The reasons for this are:

1. The simulation tool is going to be designed with the purpose to educate the effects of shading and mismatch of PV array characteristics.
2. The single-diode model is simpler to model than a two-diode model and will satisfy the purpose of constructing a simulation tool to illustrate the effects of shading and mismatch of PV arrays for renewable energy engineering education.

Chapter 2: The Modelling Process

2.1 - Choosing the program

When considering the program to choose for the modelling of the effects of shading and mismatch, considerations were made for the program which had the least complexity in modelling those effects whilst still satisfying the criteria of educating the effects of shading and mismatch of PV arrays as well as basing the model on a single-diode model.

Initially, Simulink was chosen for modelling the shading and mismatch effects. What influenced my choice in deciding to model with Simulink was that there was an existing model of a PV array based on a single-diode model created by Ben Wichert which illustrated the I-V curve. However, one thing missing in that model was the effects of incorporating a bypass diode.

2.2 - Simulink Simulations

The PV array model designed by Ben Wichert (3) modelled the power characteristics as well as the temperature characteristics of a PV array. The outputs created from this model are an I-V output of the PV array model as well as the maximum power output and the temperature output. The graphs are dependent on the ambient temperature and global irradiance surrounding the cells as well as the configuration of the module (i.e. the number of cells connected in series and parallel). My initial focus was to familiarise myself again with the Simulink program which interfaces the Matlab program.

Once that was established, the existing model of the PV array was simulated and the outputs were consistent to that seen in the literature review. Below in Figure 12 is the top layer of the PV Array model and Figure 13 and Figure 14 are illustrating the current output and power output against time of a single cell respectively.

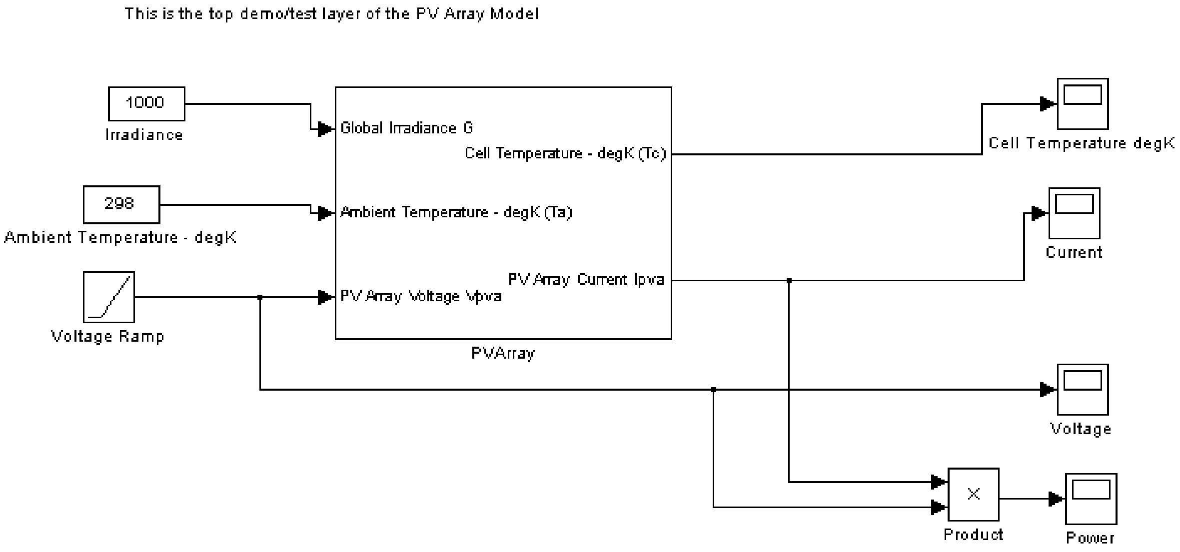


Figure 12 - Top Layer of the PV Array Model (3)

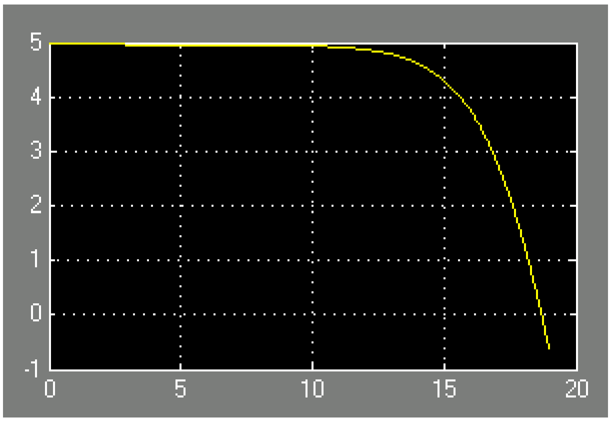


Figure 13 Current Output of a PV Cell

In Figure 13 the output is a current output of a PV array against a function of time. The time function is chosen such that it represents the voltage, so that the output authentically becomes the I-V curve.

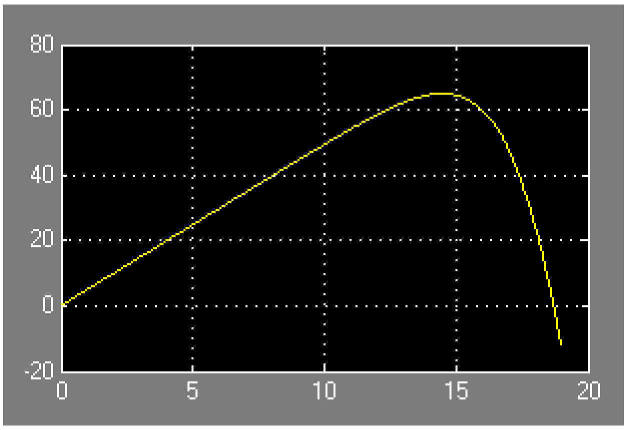


Figure 14 Power Output of a PV Cell

The bypass diode equation is easily formulated but the difficulty with Simulink is how to approach the problem of integrating bypass diodes at a specific point in the Simulink model. After establishing this problem, it was suggested to try to model the effects of shading and mismatch in ICAP.

2.3 - ICAP Simulations

ICAP is a circuit based program which has the capability of modelling electrical circuits. The initial objective was to model the I-V output of a single cell. The cell model is based on the single-diode model.

2.3.1 - Simulation of a Single Cell

The basis of the simulation of a single cell was the single-diode model. For simplification purposes only the photo-generated current (represented by a current source), diode and voltage were connected to obtain an I-V curve. Below is the circuit diagram of the initial simplified model in Figure 15.

Figure 15 - Model with diode and current source of PV Cell

For testing purposes, the photo-generated current was chosen to be an arbitrary value of 1A, the properties of the solar cell diode were unchanged from the default diode in ICAP and the voltage was defined with a ramping characteristic to illustrate the I-V curve and the ramping value was equal to 1.

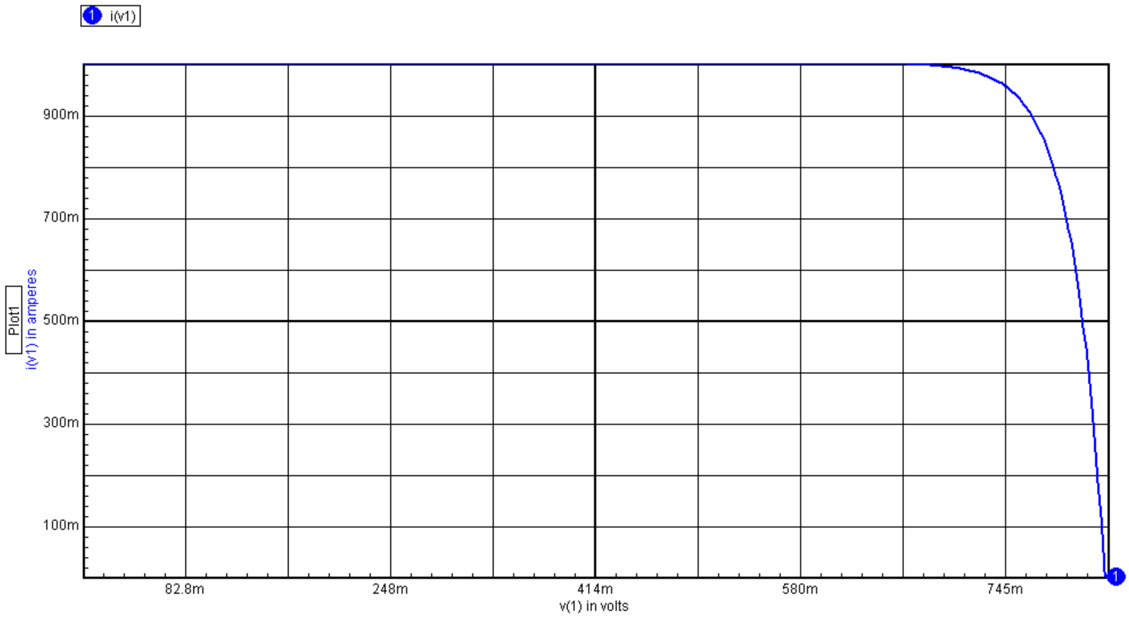


Figure 16 - I-V curve from initial model

As illustrated in Figure 16, the short circuit current output is 1A and the open circuit voltage is 0.828V.Once an I-V curve was obtained like the one in figure 16, the resistances were then added to the PV cell model in Figure 15 to build upon modelling a single-diode model.

Figure 17 - Single-Diode Model

The values of the resistances chosen were 0.005Ω and 50Ω respectively. The values chosen for the resistances are based on the values that were used in Ben Wichert's simulation in Simulink. No other values were changed from the model in Figure 17.

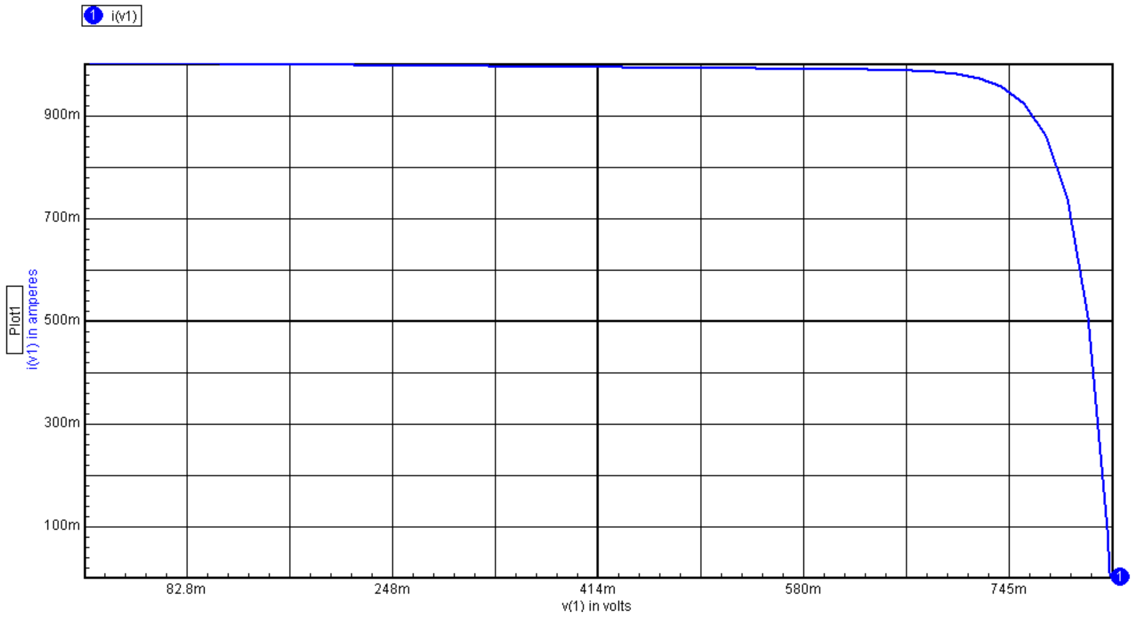


Figure 18 - I-V curve from the Single-Diode Model

As illustrated in Figure 18, the I-V curve output is the same as that of the ideal I-V curve characteristic. The short circuit current is again 1A and the open circuit voltage is approximately 828mV. After this result was obtained, a bypass diode was connected in parallel with the shunt resistance and diode. For the purposes of testing, the bypass diode characteristics were unchanged from the default diode characteristics. The diode characteristics will be further explained in Chapter 6 and definitions are provided in the glossary.

Chapter 3 - Testing in the Simulator at ROTA:

3.1 - Purpose of testing the effects of shading and mismatch of the module

The purpose of testing the effects of shading and mismatch of a module in an existing simulator was to obtain I-V curve outputs for the following scenarios:

- Shaded module with bypass diode connections
- Shaded module without bypass diode connections
- Unshaded module with bypass diode connections
- Unshaded module without bypass diode connections

The testing conditions were in a testing compound in an ambient temperature surrounding of approximately 25°C. When testing the I-V curves, the testing conditions of the module were all cells unshaded, one cell fully shaded and varying degrees of one cell being partially shaded. The shading conditions were also tested on the module with and without the bypass diodes connected. The purpose for this was to test the effects that the bypass diodes had on a module when a cell of a module was exposed to shading and confirm that the outputs were consistent to that of previous studies. This will be elaborated further in chapter 4 and Appendix B.

3.2 - Module chosen for testing:

The module chosen for testing was a standard 36 cell module with 2 bypass diodes connected across 18 cells. The BP Solar BP275F module fitted the criteria of being a standard mono-crystalline module. In the table below, there are the measured values under standard testing conditions (STC) on the nameplate of the BP275F module.

BP Solar BP275F Module	
Variables on Nameplate:	Measured Values on Nameplate Under STC
Nominal Peak Power (Pmax)	75W
Peak Power Voltage (Vmp)	17V
Peak Power Current (Imp)	4.45A
Short Circuit Current (Isc)	4.75A
Open Circuit Voltage (Voc)	21.40V
Minimum Power (Pmin)	70W

Table 1 - Nameplate values on BP275F Module

3.3 - Experimental Setup:

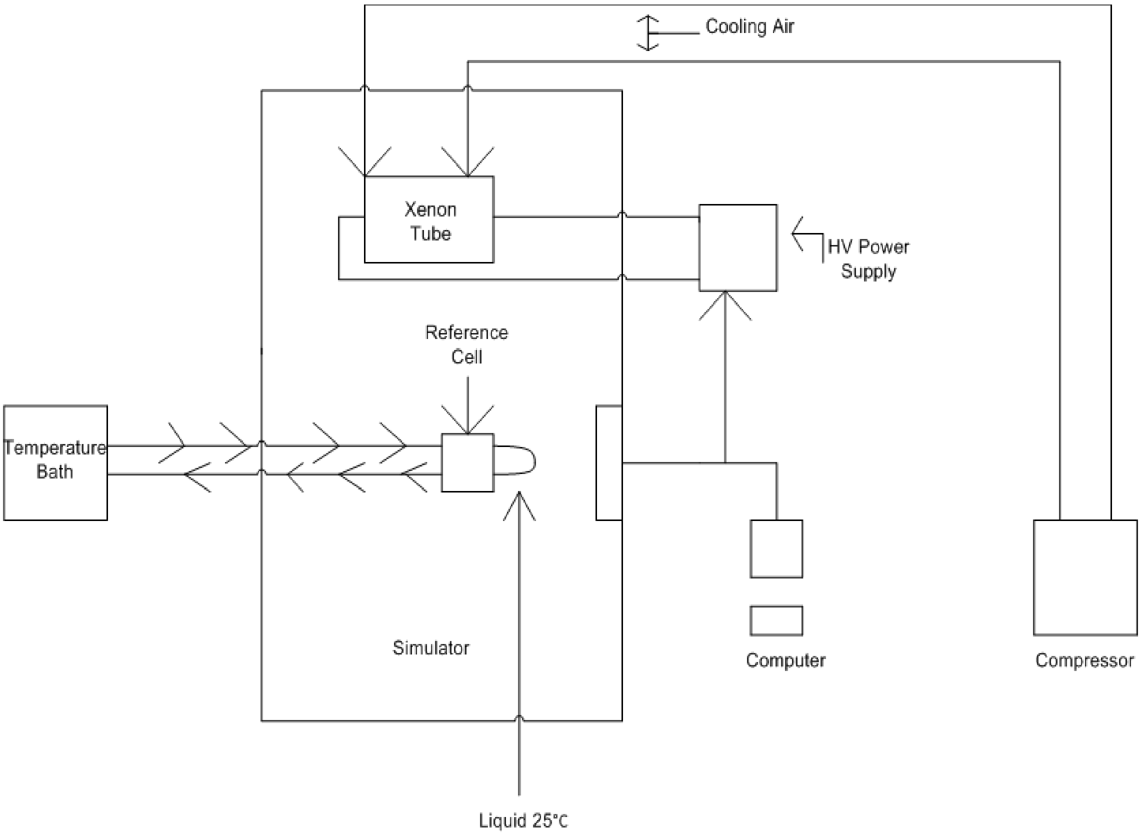


Figure 19 - Experimental setup for the testing at the ROTA compound.

The specifications of the SPI-SUN Simulator 460 are described in further detail in Appendix A.

3.4 - Theory of operation of the SPI-SUN Simulator 460

3.4.1 - Xenon Lamp and Spectral Filter

A xenon tube is essentially a strobe light and this will output 150 pulses every time a simulation is run. Each pulse is sent back to the computer and recorded as a reading. Hence, each run performed will have 150 readings recorded. The reasons why a xenon tube is used in the Spi-Sun Simulator 460 to generate light over the module are that its spectral distribution is closer to the sun than that of incandescent light bulbs and the xenon tube does not heat the modules when simulations are performed.

3.4.2 - Standard Cell

"A standard cell is included as a calibrated reference for the absolute light intensity. This cell has been cut to 4cm^2 area and mounted according to the approved ASTM (American Society for Testing and Materials) specifications. A thermocouple has been integrally mounted with the cell for displaying cell temperature on the CRT monitor.

The standard cell calibration has been performed according to ASTM (American Society for Testing and Materials) specifications.

The standard cell is essential to the operation of the electronic load due to the pulsed nature of the light source. When the variable light intensity of the pulse crosses the trigger level preset (by the computer) for the standard cell in the electronic load, a sample of the current and voltage across the panel is taken. This sample is held until the next light flash and then updated. "(12)

3.4.3 - Panel Temperature

"The panel temperature is sensed by an optical thermal sensor which is located in the base of the cart. The output is connected to the computer and merged with temperature coefficients to make corrections to the I-V curve. "(12)

3.5 - Computer and Sun Simulator Operating Software

"The computer system in the SPI-SUN Simulator 460 controls both the operation of the Sun Simulator and processes solar module performance data. The components included in the computer system are a personal computer, keyboard, monitor, floppy disk drive, internal hard drive and printer.

The control functions of the computer include enabling the xenon lamps, setting the lamp intensity, setting the electronic load current scale, settling the electronic load voltage scale and setting the level of irradiance at which module measurements are made. The data processing functions include input of the module I-V curve in the form of 50-200 pairs from short circuit current to open circuit voltage, a graphic display of the curve, calculation and display of all important performance parameters, display of temperature, irradiance, module serial number, date and time. The menu-driven software allows module data to be corrected to any temperature, printed out, saved to a floppy disk and loaded from a floppy disk." (13)

3.6 - Compressor

The compressor in the system setup provides cool air to flow to the xenon tube.

3.7 - Temperature Bath:

The temperature bath feeds coolant through a tube via the reference cell at a temperature of 25°C. This is to maintain standard testing conditions (STC) during the testing of the module.

Chapter 4 – Results from the ROTA simulations:

4.1 – Results with Bypass Diode Connection

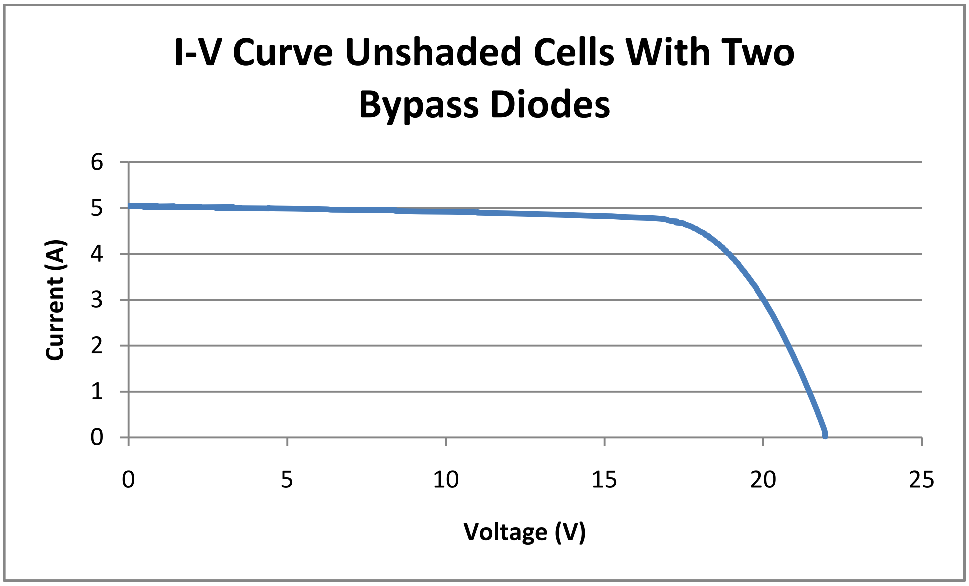


Figure 20 I-V Curve of an unshaded module with two bypass diodes connected

The graph in Figure 20 illustrates the I-V curve output of an unshaded BP275F module with two bypass diodes connected. As can be observed the output of the I-V curve looks like the ideal I-V curve characteristic. The short circuit current output is approximately 5.05A and the open circuit voltage is approximately 21.9V.

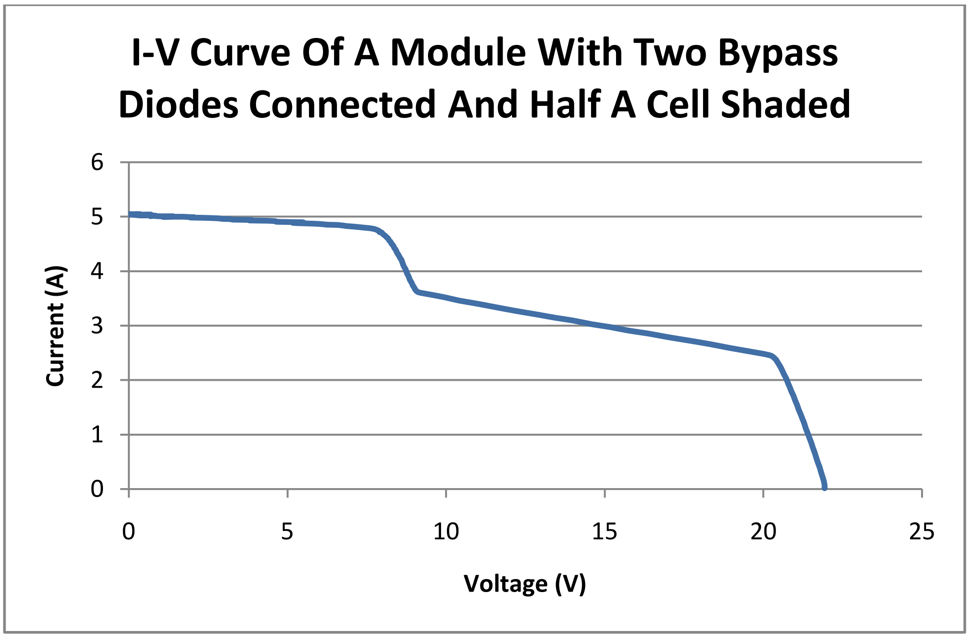


Figure 21 I-V Curve of a module connected with two bypass diodes with a single cell half shaded

The graph in Figure 21 illustrates the I-V curve output of a BP275F module with half a cell shaded. The BP275F module has 36 cells with 2 bypass diodes connected in parallel with the cells. One bypass diode is connected in parallel with 18 cells. The short circuit current is the same value as that for the unshaded condition. However, at about halfway along the voltage in the x-axis, there is a drop in the current output in the y-axis.

The reason for this output is that the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. However, the dip in the curve at about the halfway point of the I-V curve is a result of the partial shading coming into effect.

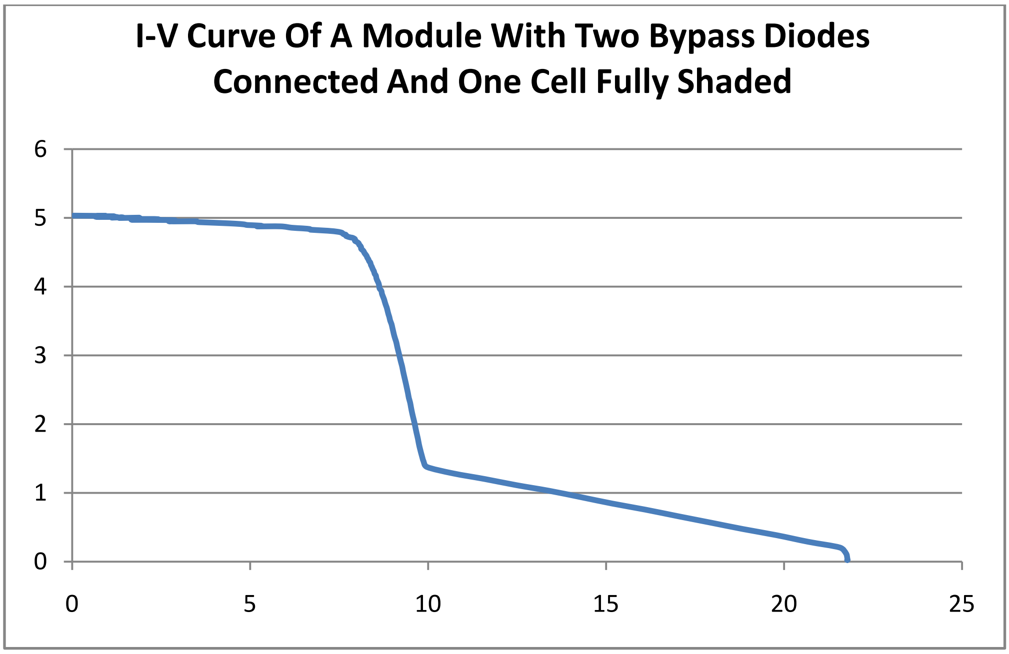


Figure 22 - I-V Curve of a module with two bypass diodes connected and one cell fully shaded

The graph in Figure 22 illustrates the I-V curve output of a BP275F module with one cell fully shaded. The BP275F module has 36 cells with 2 bypass diodes connected in parallel with the cells. One bypass diode is connected in parallel with 18 cells. The short circuit current is the same value as that for the unshaded condition. However, at about halfway along the voltage in the x-axis, there is a more significant drop in the current output in the fully shaded condition than that in the half shaded condition in the y-axis.

The reason for this output is that the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. However, the dip in the curve at about the halfway point of the I-V curve is a result of the partial shading coming into effect.

4.2 - Results without Bypass Diode Connection

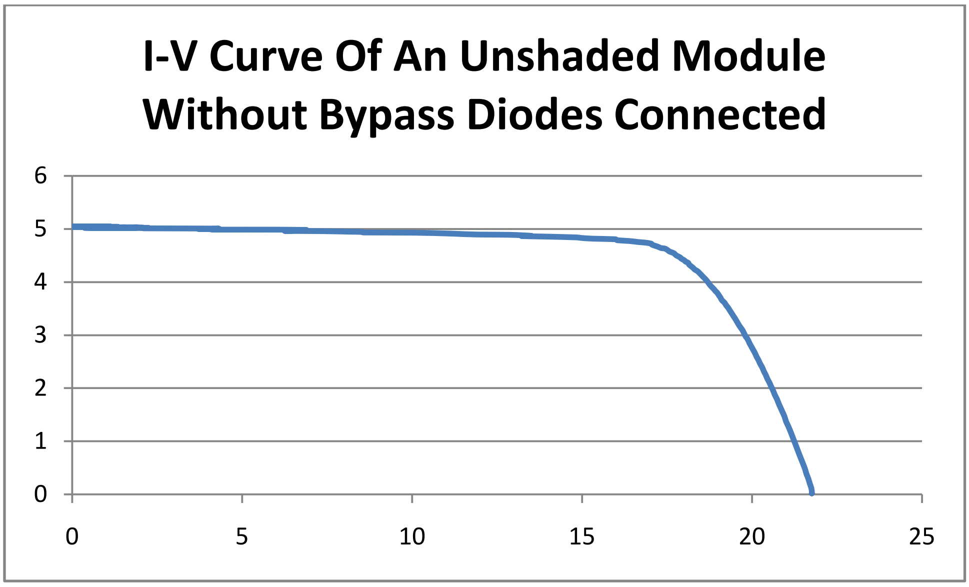


Figure 23 - I-V curve of an unshaded module without bypass diodes connected

The graph in Figure 23 illustrates the I-V curve output of an unshaded BP275F module without bypass diodes connection. As can be observed the output of the I-V curve looks like the ideal I-V curve characteristic. There is no change in this output compared to the I-V curve output of an unshaded BP275F module with two bypass diodes connected.

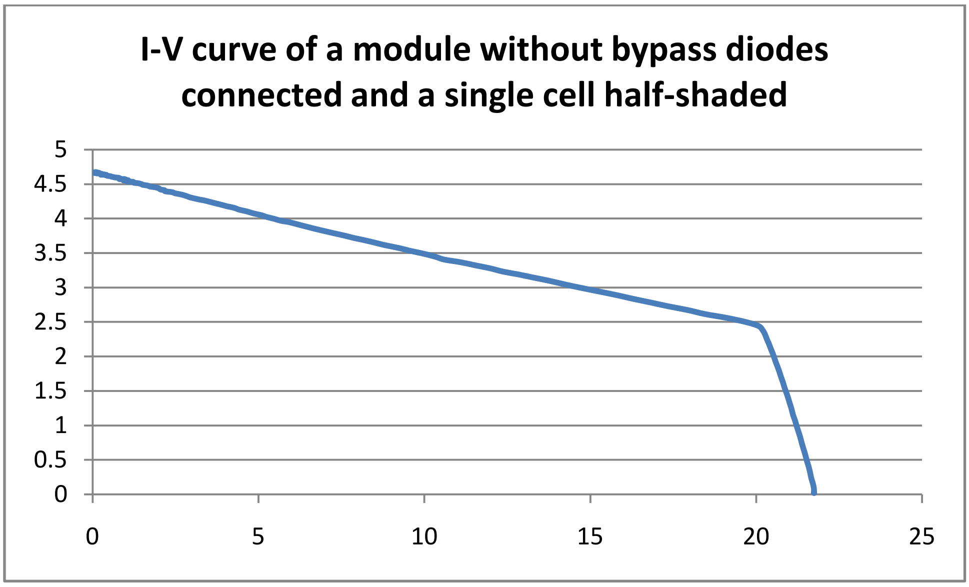


Figure 24 - I-V curve of a module without bypass diodes connected and a single cell half-shaded

The graph in Figure 24 illustrates the I-V curve output of a BP275F module with half a cell shaded. The BP275F module has 36 cells without bypass diode connection in this instance. The short circuit current is lower than that of the unshaded condition at 4.67A. The output expected in Figure 24 is different to that of the actual output because the short circuit current is just above 4.5A. Whereas, the expected short circuit current for a module with a cell half shaded without bypass diode connection should be close to 2.5A. This is because the short circuit current of the combined cells should fall to the lowest short circuit current output of the module. The higher than expected short circuit current values in Figures 24 and 25 may be an issue with the residual charge.

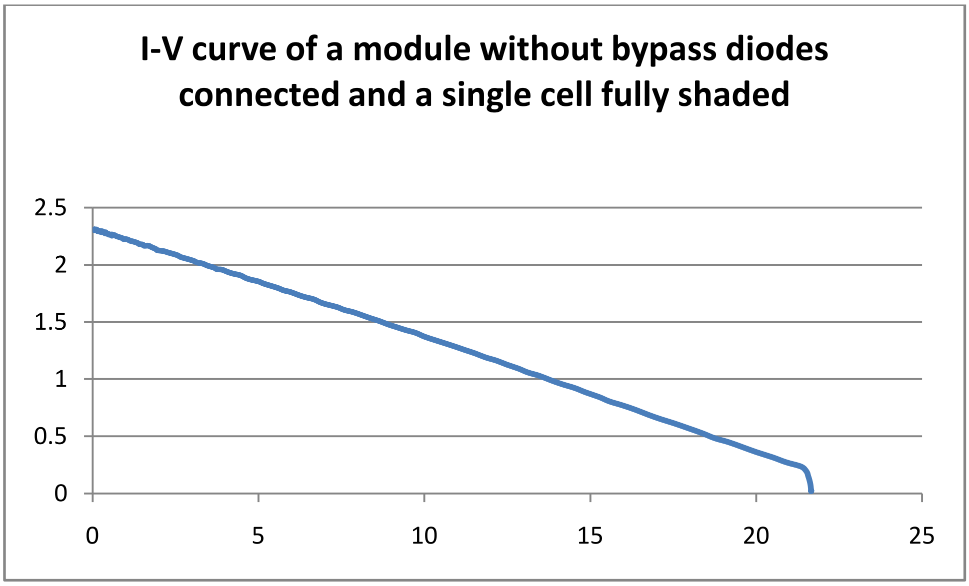


Figure 25 - I-V curve of a module without bypass diodes connected and a single cell fully shaded

The graph in Figure 25 illustrates the I-V curve output of a BP275F module with half a cell shaded. The BP275F module has 36 cells without bypass diode connection in this instance. The short circuit current is lower than that of the unshaded condition. The output expected in Figure 25 is different to that of the actual output because the short circuit current is just above 2A. Whereas, the expected short circuit current for a module with a cell fully shaded without bypass diode connection should be close to 0A. This is because the short circuit current of the combined cells should fall to the lowest short circuit current output of the module.

Chapter 5 – The Curve Fitting Process to Obtain the Modified Parameters to input into the ICAP Model:

Once results were obtained from the ROTA compound, the results were converted to Microsoft Excel using a Curves executable file. The Curves executable file is used to convert DAT files into text delimited files which then can be opened by Microsoft Excel.

Once the unshaded results of the module without bypass diode connections were converted to Microsoft Excel, the measured voltage and current of those results were copied into a PV Module Curve Fitting file in Microsoft Excel. There was also a calculated current equation which was input into Microsoft Excel which was based on the single-diode equation.

$$I = I_{ph} - I_O\left(\frac{q\times(\frac{V_m}{S_C}+I_m\times\frac{R_s}{1000})}{(k+(T_c+273)-1)}\right) - \frac{(\frac{V_m}{S_C}+I_m\times\frac{R_s}{1000})}{R_p}$$

The parameters for the single diode equation are:

I = Calculated Cell Current (A)

Iph = Photo-generated Current (A)

Io = Diode Saturation Current (A)

Tc = Cell Temperature (°C)

q = Unit Charge (C)

k = Boltzmann’s Constant (J/K)

Rs = Cell Series Resistance (mΩ)

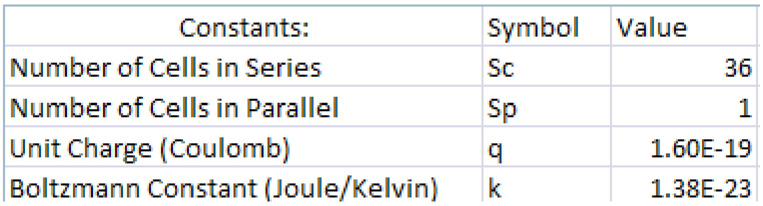
Rp = Cell Parallel/Shunt Resistance (Ω)

Sc = Number of Cells in Series

Vm = Measured Voltage

Im = Measured Current

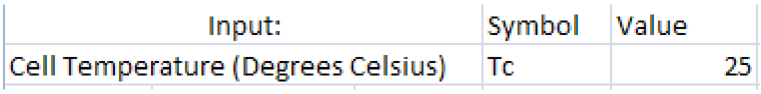
The parameters that are constant and do not need modifying in table 2 are:



Constants:	Symbol	Value
Number of Cells in Series	Sc	36
Number of Cells in Parallel	Sp	1
Unit Charge (Coulomb)	q	1.60E-19
Boltzmann Constant (Joule/Kelvin)	k	1.38E-23

Table 2 - Constant Parameters in Curve-Fitting Model in Microsoft Excel

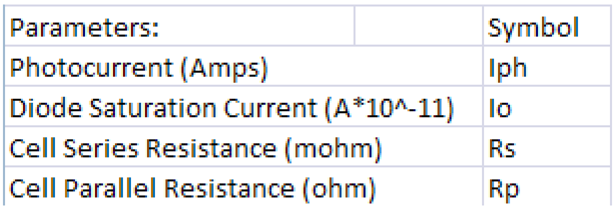
The input for this PV curve fitting model is the cell temperature. The outputs of a module are dependent on the effects of the changes in temperature. An increase in cell temperature will correspond to an increase in the voltage output as well as a slight increase in current output. Below in Table 3 is a table of the cell temperature at standard testing conditions (STC).



Input:	Symbol	Value
Cell Temperature (Degrees Celsius)	Tc	25

Table 3 - Cell Temperature Input

Therefore, the parameters that need to be modified in the ICAP model via the curve fitting in Microsoft Excel in Table 4 are:



Parameters:	Symbol
Photocurrent (Amps)	Iph
Diode Saturation Current (A*10^-11)	Io
Cell Series Resistance (mohm)	Rs
Cell Parallel Resistance (ohm)	Rp

Table 4 - Parameters to be modified in ICAP Model

The cell series and parallel resistance values measured at the ROTA compound are 588mΩ and 75.95Ω respectively. To calculate the modified photo-generated current and diode saturation current, a solver function was used to calculate the least errors square function of the curve. The equation of the error square function is:

Error Square = (Im - I(Calculated))^2

Where:

Im is the measured current

I (Calculated) is the calculated current

From there, the photo-generated current and the diode saturation current are calculated using the solver function in Microsoft excel and this is based on a sum of the minimum error square function in the order of 0.1. For the scenario without bypass diodes this calculates a Photo-generated current of 5.048828A and a Diode Saturation current of 2.02 *10^-12 A.

These modified values are input into the ICAP model and the results will be explained further in chapter 6.

Chapter 6 – Duplicating results from ROTA simulation to ICAP model:

To duplicate the results from the ROTA simulation into the ICAP model, curve fitting which was explained in chapter 5 was performed. Once the values were obtained from the curve fitting process, they were input into the modified model in ICAP.

For the ICAP model without bypass diode connection, the values that were input into the ICAP model were as follows:

Series resistance of 588mohms

Parallel resistance of 75.97 ohms

Photo-generated current of 5.04 Amps

Diode saturation current of 2.02 *10^-12 Amps

The resistance values and the photocurrent value were input into each solar cell. The diode saturation current is also input into each solar cell diode. Once those values were input into the ICAP model of a module without bypass diode connection, a simulation was run. Whilst, the short circuit current was approximately the same as that of the photo-generated current, the open circuit voltage was much greater than that of the corresponding open circuit voltage for the ROTA simulation. What was established after this simulation was that the diode characteristics needed to be further modified for the ICAP output to more closely resemble the ROTA output. The Diode characteristics in ICAP are in the table below along with the default values:

Type	**Diode Parameters**	Default Values in ICAP/4
AF	Flicker noise exponent	1
BV	Reverse	Inf

	Breakdown Voltage	
CJO	zero-bias junction capacitance	0
EG	activation energy (eV) (Bandgap for Semi-conductor Material)	1.11 for silicon
FC	Co-efficient for Forward-Bias	0.5
IBV	Current at Breakdown Voltage	- 10^-3
IS	Saturated Current	1.0e^-14
KF	flicker noise coefficient	0
M	Grading Co-efficient	0.5
N	Emission Co-efficient	1
RS	Ohmic Resistance	0
TNOM	Parameter measurement temp. (°C)	27
TT	transit-time (sec)	0
VJ	junction potential	1
XTI	Saturation-current temp. exp. - 3.0 3.0 jn. 2.0 Sbd	3.0 pn Junction diode 2.0 for SBD

Table 5 - Table of Diode Characteristics

The Definition of the Diode Characteristics is explained in the Glossary section of the Thesis.

To modify the I-V curve, the DC characteristics of the diode were required to be modified. The DC characteristics of the diode are the saturation current (Is), Emission co-efficient (n) and the ohmic resistance (Rs).

The increase in the default saturation current had partially reduced the open circuit voltage output, but this was still greater than the simulated output. This left the ohmic resistance and emission co-efficient values which may have needed to be modified as all of the other diode parameters would have no bearing on influencing the output of the I-V curve of the module.

The emission co-efficient is also known as the ideality factor. Typically the ideality factor value is between 1 and 2. By trying to mimic the I-V curve of the BP275F module, the value of the emission co-efficient input into the solar cell model was changed from a default value of 1 to 0.9. This is clearly an anomaly and is inconsistent with the typical ideality factor value.

Chapter 7 – Comparison between the Results from the ROTA Simulation and the ICAP Model

7.1 – Comparison of Results with Bypass Diode Connection

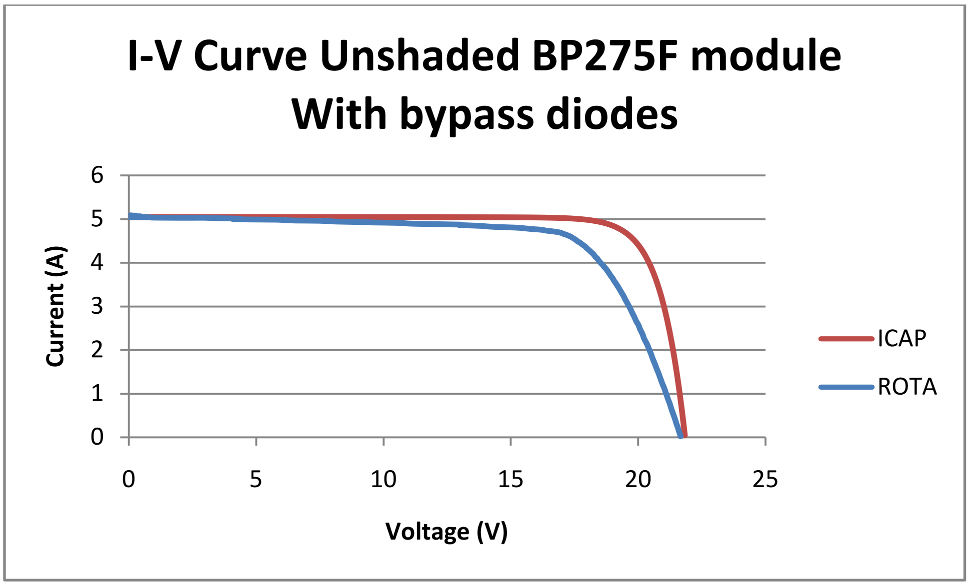


Figure 26 - I-V Curve of an Unshaded BP275F Module With Bypass Diodes

The outputs in the above graph in Figure 26 depict I-V curves of an unshaded BP275F module with two bypass diodes connected. The red curve denotes the ICAP results and the blue curve denotes the ROTA results. Even though the short circuit current output and the open circuit voltage outputs for the ICAP and ROTA results are the same, there is a discrepancy with the maximum power point of the two curves. The reason for this discrepancy is that the ROTA results are based on a different set of algorithms to the ICAP program.

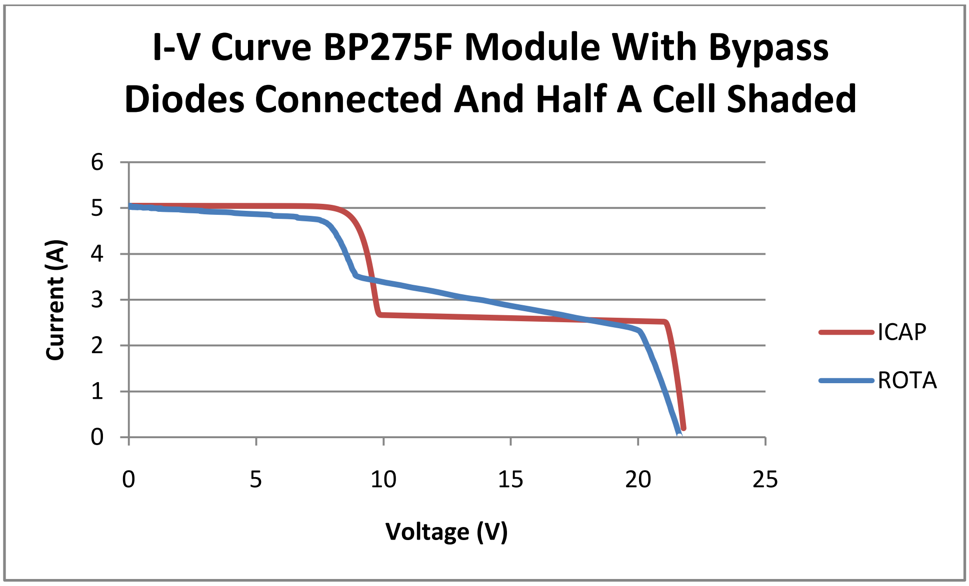


Figure 27 I-V Curve of an Unshaded BP275F Module With Bypass Diodes and Half A Cell Shaded

The outputs in the above graph in Figure 27 depict I-V curves of a BP275F module with two bypass diodes connected and half a cell shaded. The red curve denotes the ICAP results and the blue curve denotes the ROTA results. In the ICAP model this was modelled by halving the photo-generated current of one of the cells. In the ROTA compound, the shading was simulated by covering half a cell of the BP275F module with cardboard and sticking masking tape from the cardboard to the module. The visual depiction of the shading of the module is documented in more detail in Appendix C.

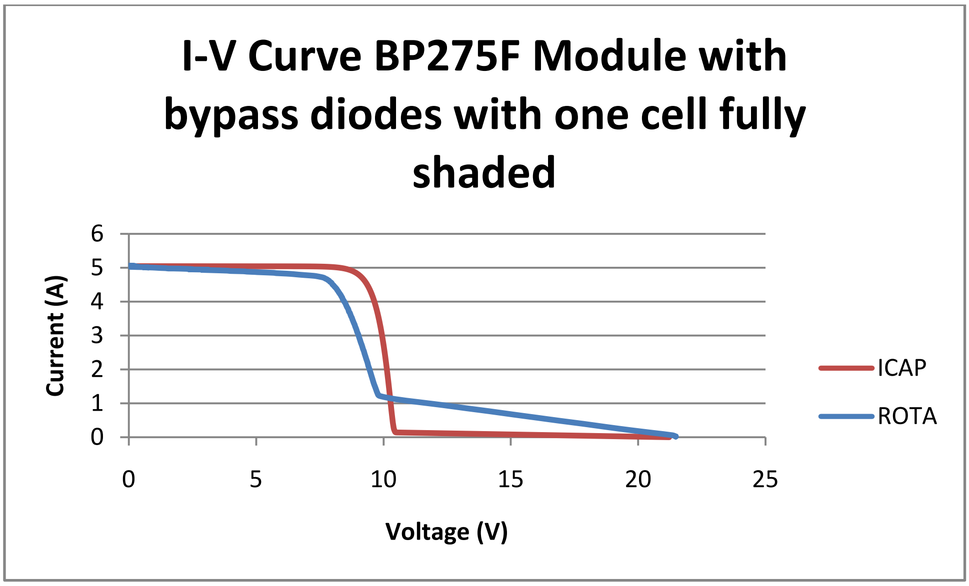


Figure 28 - I-V Curve of an Unshaded BP275F Module With Bypass Diodes And One Cell Fully Shaded

The outputs in the above graph in Figure 28 depict I-V curves of a BP275F module with two bypass diodes connected and one cell shaded. The red curve denotes the ICAP results and the blue curve denotes the ROTA results. In the ICAP model this was modelled by changing the photo-generated current of one of the cells zero. In the ROTA compound, the shading was simulated by covering half a cell of the BP275F module with cardboard and sticking masking tape from the cardboard to the module.

7.2 – Comparison of Results without Bypass Diode Connection

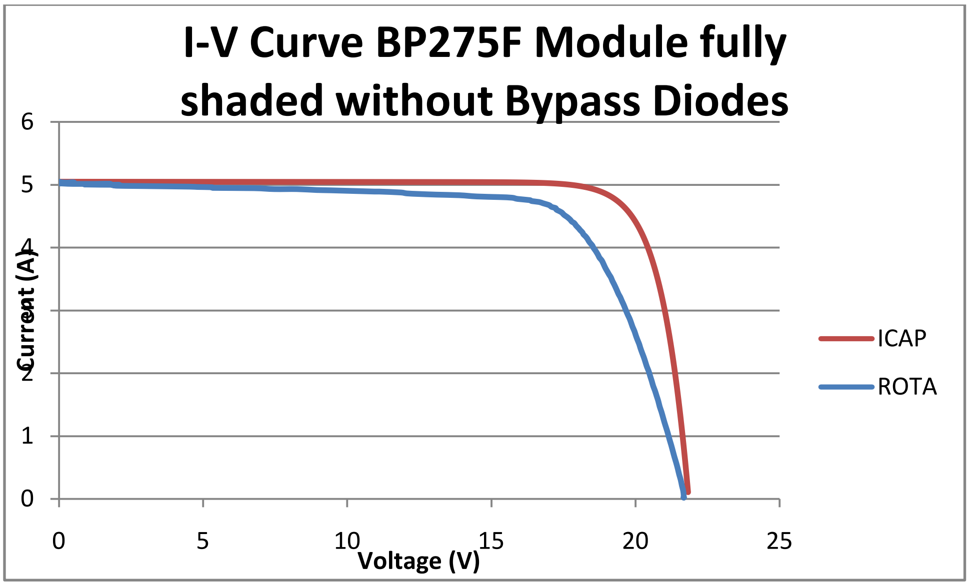


Figure 29 - I-V Curve of an Unshaded BP275F Module Without Bypass Diodes

The outputs in the above graph in figure 29 depict I-V curves of an unshaded BP275F module without bypass diode connection. The red curve denotes the ICAP results and the blue curve denotes the ROTA results. As can be observed in Figure 29 the I-V curve output is the same as that for the unshaded condition of the BP275F module with bypass diode connection and has the same shape as that of the ideal I-V curve characteristic. Even though the short circuit current output and the open circuit voltage outputs for the ICAP and ROTA results are the same, there is a discrepancy with the maximum power point of the two curves.

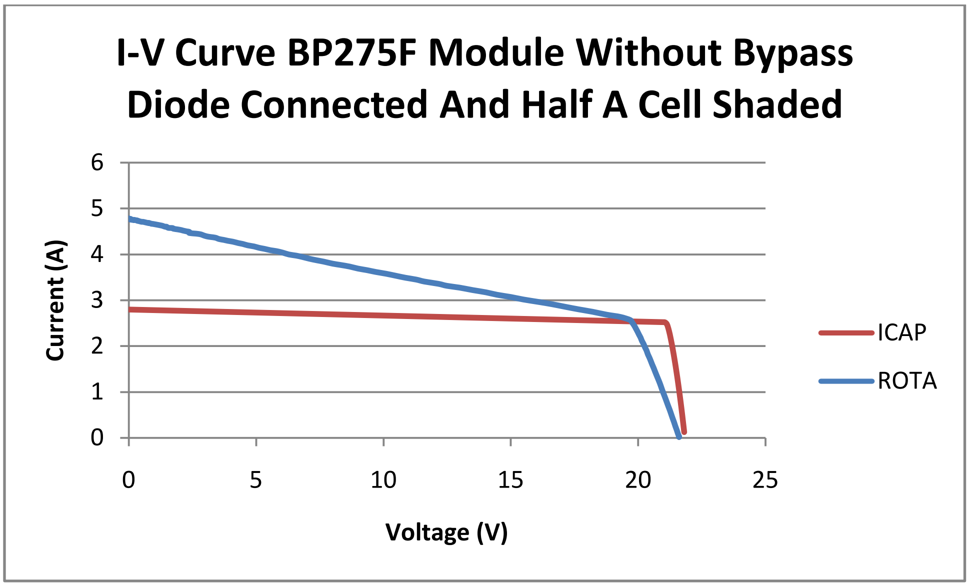


Figure 30 - I-V Curve of a BP275F Module without Bypass Diodes and Half a Cell Shaded

The outputs in the above graph in Figure 30 depict I-V curves of a BP275F module with two bypass diodes connected and half a cell shaded. In the ICAP model this was modelled by halving the photo-generated current of one of the cells. The short circuit current output for the half shaded ICAP result is just over half that of the unshaded result. However, the short circuit of the ROTA simulation is over 4A and there is a very noticeable ramping characteristic associated with this curve. A subsequent test was conducted at the ROTA compound to verify the results. The results for the second set of ROTA simulations proved to the same as that for the first set of simulations. This will be elaborated further in Appendix C.

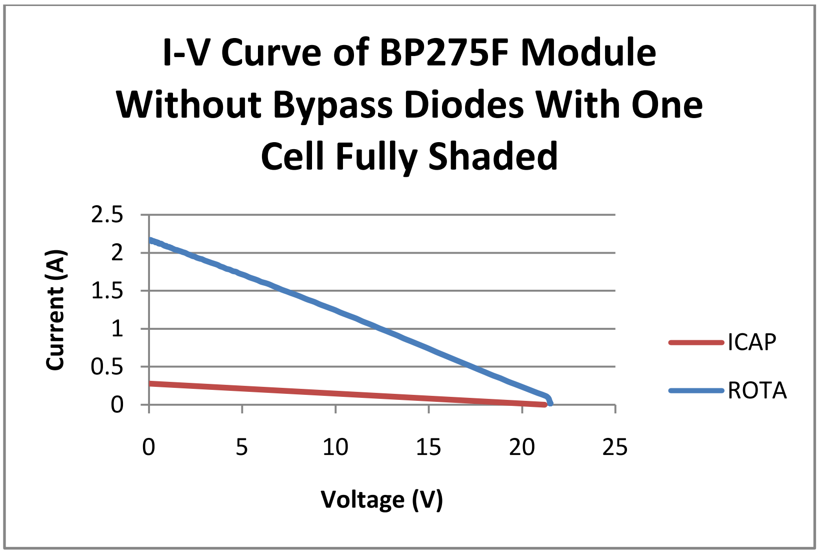


Figure 31 - I-V Curve of a BP275F Module without Bypass Diodes and One Cell fully Shaded

The outputs in the above graph in Figure 31 depict I-V curves of a BP275F module with two bypass diodes connected and half a cell shaded. In the ICAP model this was modelled by changing the photo-generated current of one of the cells to Zero. The short circuit current output for the fully shaded ICAP result is approximately 280mA which is significantly less than that for the unshaded result. However, the short circuit of the ROTA simulation is over 2A and there is a very noticeable ramping characteristic associated with this curve. A subsequent test was conducted at the ROTA compound to verify the results. The results for the second set of ROTA simulations proved to the same as that for the first set of simulations. This will be elaborated on further in Appendix C.

Conclusions:

This project was devoted to building a simulation tool that illustrates the effects of shading and mismatch within a photovoltaic array. The target audience for this simulation tool was to educate renewable energy engineering students. The project aims at the commencement of this project were:

- To review the availability and capabilities of existing software and tools to illustrate the effects of shading and mismatch.
- Develop a model based on either a single-diode model or a two-diode model.
- Include bypass diodes in this model to illustrate the effects of shading and mismatch.
- Evaluate and compare the simulation model against actual PV measurements.
- Incorporate the cell model into modules and arrays.

The program chosen to build my simulation model was ICAP/4 which is a circuit based program because it was easier to implement bypass diodes at a specific point in the program than in the Simulink model. A single diode model was chosen to be used for the basis of building a solar cell instead of the two diode model because the single diode model was not as complex to model as a two diode model and it helped fulfil the purpose of constructing a simulation tool to illustrate the effects of shading and mismatch of PV arrays for renewable energy engineering education.

Once the single cell was successfully modelled, this was then expanded into a 36 cell module with and without bypass diode connection to successfully model the effects of shading and mismatch using ICAP/4. As explained in chapters 4, and 8, shading and mismatch on a partially shaded cell within a module were demonstrated to have a reduction of a power output from the module compared to unshaded conditions. The results of the different degrees of shading of a cell within a module with bypass diode connection demonstrated that there was no change in the short circuit current because the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. However, the dip which occurred at approximately the halfway point of the I-V curve is a result of the partial shading coming into effect and the value of the current drops depending on the degree of shading on a cell.

The results of the module without bypass diode connection demonstrated a greater reduction of power output compared with the results with bypass diode connection and this is because a bypass diode limits the reverse bias voltage of a shaded cell. The short circuit current output was reduced for the shaded results without the bypass diode connection and this is due to the short circuit current output of a combination of cells falling to the lowest short circuit current output which is the output of the shaded cell.

The effects of shading and mismatch were to a degree successfully modelled in ICAP/4 because the shape of the I-V Curves in the results section were similar to that of the curves in the background section and were quite similar to ROTA. When comparing the outputs of the I-V curves from ICAP with the I-V curves from ROTA the short circuit currents and open circuit voltages were very similar. But there was some disparity with the different curves. This was most noticeable with the shaded results for a BP275F module without bypass diode connection where the short circuit current values were much higher for the ROTA results than for the ICAP results and there was also a more noticeable ramping characteristic with the ROTA results than the ICAP results. At this point this anomaly requires further investigation to provide a satisfactory answer and may be suitable for another thesis project.

Although there was some success modelling the effects of shading and mismatch of a module, given the time constraints of the project I was unsuccessful with incorporating the cell model into an array model. The text in the next section offers some suggestions to enhance this project.

Recommendations for Further Work:

As outlined in the conclusion many of the objectives were completed for this project. However, there is plenty of scope for expansion. I believe that this project could be enhanced from the following recommendations:

- Build upon the work of simulating a module in ICAP by modelling the shading and mismatch effects of an array.
- Investigate how to implement the bypass diode into Ben Wichert’s existing single cell model in Simulink to illustrate the effects of shading and mismatch of photovoltaic arrays.
- Use a wide range of software to build the single-diode model and illustrate the effects of shading and mismatch. The majority of my work consisted of utilising the ICAP software.
- Only mono-crystalline modules were used for the testing of shading and mismatch. There could be scope to develop a simulation model with the capability of modelling the effects of shading and mismatch with different types of modules.

- There were some anomalies with the short circuit current results obtained from the testing at the ROTA compound. There was a second test conducted at the ROTA compound to check if the results obtained were the same. As the results were the same as the first test results, I have done some investigation but have been unable to find a satisfactory explanation for the high short circuit current outputs for the shaded conditions of the module without bypass diodes. There may be potential for a future thesis project.

Considering the list of possible recommendations, it is clear that there is a significant capacity for future work on this project. This list of suggestions provided is by no means exhaustive and each point has the potential to build additional work.

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Appendices:

Appendix A: SPI-SUN Simulator 460 Specifications

Below in Table 6 are the specifications of the SPI-SUN Simulator 460.

Maximum Module Dimensions:	
Length	200cm
Width	137cm
Height	7.6cm
Light Source:	
Long- arc pulsed xenon lamp, filtered to AM 1.5 Global Spectrum (ASTM E927)	
Intensity Range	70 - 110 mW/cm^2
Lamp Lifetime, typical	1000 hrs
Illumination Uniformity	±3% over test area
Measurement Ranges:	
Voltage (3 ranges)	2, 25 and 100V
Current (2 ranges)	2 and 20A
Resolution (on most sensitive ranges):	
Voltage	0.0005V
Current	0.0005A
Equipment Dimensions (Excluding Computer System):	
Width	323cm
Depth	155cm
Height	274cm
Equipment Weight, Net	850Kg
Utilities Requirements:	
Electricity	190-240 VAC, 30A, 50/60Hz, single phase
Compressed Air	140 L/min at 275kPa (% scfm at 80 psi)

Table 6 - Specifications of the SPI-SUN Simulator 460 Specifications (11)

Appendix B: Operating Instructions of the Spi-Sun Simulator 460

These are the operating instructions that were used to perform the simulations of various shading conditions of a PV module with and without bypass diode connection.

1.) "Press the HV On switch which is located on the electronics cabinet control panel. This will activate the lamp cooling blower located on top of the tower and the compressed air solenoid for cooling lamp ends and latched via a K3 relay mounted in the AC distribution box if all interlocks are satisfied. However, if the latch is unsuccessful, check all interlocks. To disable the high voltage, press HV off switch on the control panel.
2.) The height of the standard cell is adjustable and should be adjusted to match the height of the solar cells in the module being tested. The reference cell height can be adjusted by loosening the knob (underneath the cell) and sliding the reference cell package to the desired position.
3.) Three long sliding bars are located on the module cart. Large black knobs on the ends of each bar can be turned to unlock these support bars to permit movement to match the dimensions of the panel. The location of the sliding bars should be adjusted to approximately centre the panel in the test plane or to place the panel in a convenient location for attaching the test leads.
4.) The bars should be adjusted to match the shape of the panel and to clear any protruding connectors or junction boxes on the underside of the panel. Power connections can then be made. The labels over the terminals on the centre bar indicate the positive and negative connections. The four terminals correspond to two separate voltage and two current terminals.
5.) Push in the cart. The connector at the rear end of the cart will connect with a socket mounted in the base of the tower. Once the cart is pushed in and the connection is made, an I-V measurement can be taken.
6.) The computer controls most of the simulator functions which include when to flash, trigger level (irradiance at which I-V data is sampled and held), peak light intensity and selection of the proper current and voltage ranges for the electronic load.
7.) The operator chooses from menus whether to input module or test parameters (such as number of cells, temperature correction coefficients or irradiance level), test a cell or panel, print data, store data or retrieve data." (14)

Appendix C: the Shading results obtained from ROTA

As there was an anomaly with the first set of tested simulated results regarding the short circuit current for the shaded conditions of the module without bypass diode connections, compared with the simulated results in ICAP another test was conducted to verify the results from the SPI-SUN Solar Simulator 460.

The shading of the modules was conducted in the SPI-SUN Solar simulator 460. Some cardboard was used to simulate the effects of a load across a cell within a module. No masking tape was used to secure the cardboard on the module for the first set of testing conducted on the BP275F module. The module was mounted and secured on the tray inside the simulator.

This time masking tape was used to secure the cardboard on the module. The subsequent photos of the various shading conditions depict how the module was shaded in the second set of testing.

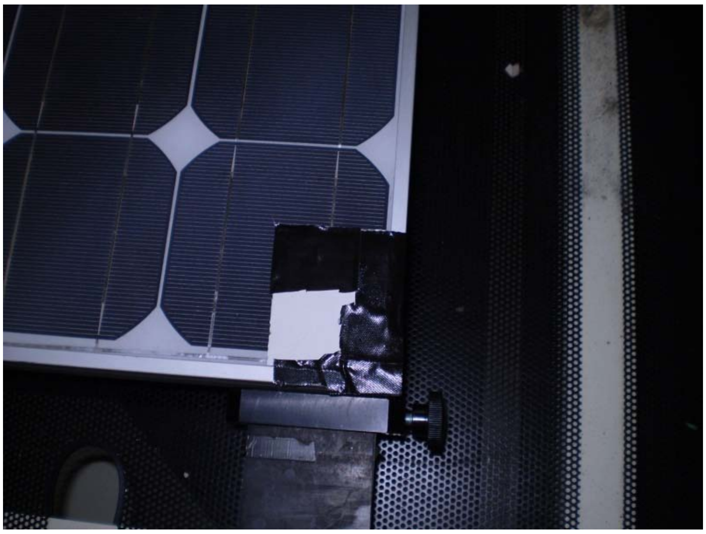

Figure 32 BP275F Module with a Quarter of a Cell Shaded

The picture in Figure 32 is a module which has a quarter of a cell shaded. This is simulated by using cardboard to cover the cell and masking tape to secure the covered cell. The results of the repeated test for the shading scenario in Figure 32 are illustrated in Figure 33 and Figure 34 below.

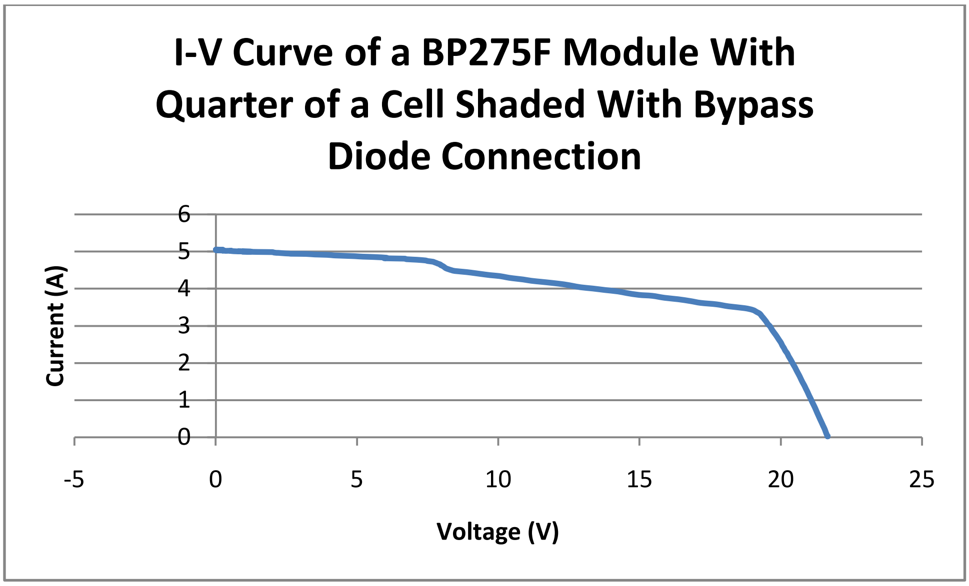

Figure 33 - I-V Curve of a BP275F Module with a Quarter of a Cell Shaded With Bypass Diode Connection

The outputted I-V curve in Figure 33 illustrates the I-V Curve of a BP275F module with a quarter of a cell shaded with two bypass diodes connected.

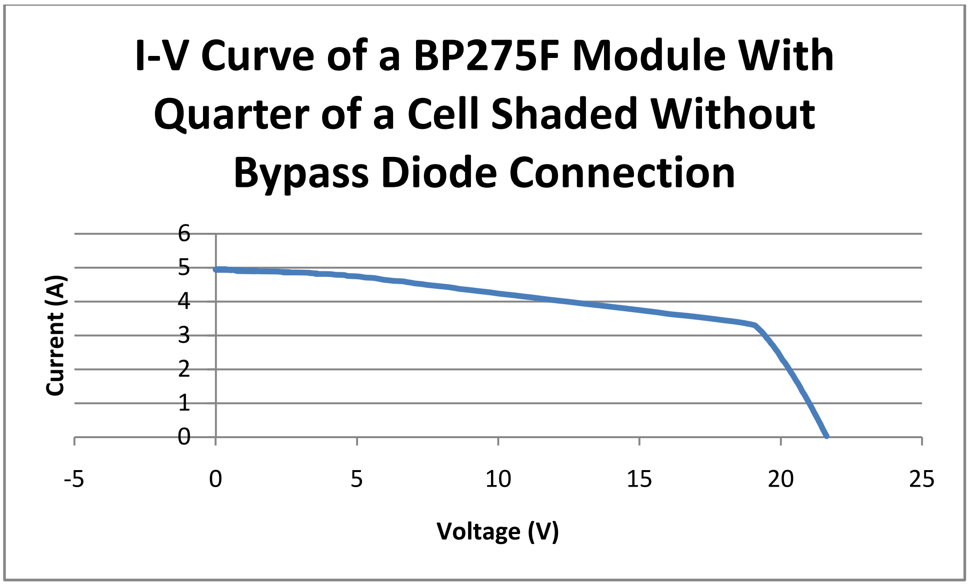

Figure 34 - I-V Curve of a BP275F Module With a Quarter of a Cell Shaded Without Bypass Diode Connection

The outputted I-V curve in Figure 34 illustrates the output of a BP275F Module without bypass diode connection and with a quarter of a cell shaded. The output expected in Figure 34 is different to that of the actual output because the short circuit current is approximately 5A. Whereas, the expected short circuit current for a module with a quarter of a cell shaded without bypass diode connection should be approximately three quarters of the short circuit current for the unshaded condition. This is because the short circuit current of the combined cells should fall to the lowest short circuit current output of the module.

In addition to this, there were two different scenarios for half a cell shaded of a module. That is, one cell half shaded horizontally and one cell half shaded vertically. The shading simulations are represented in the figures below.

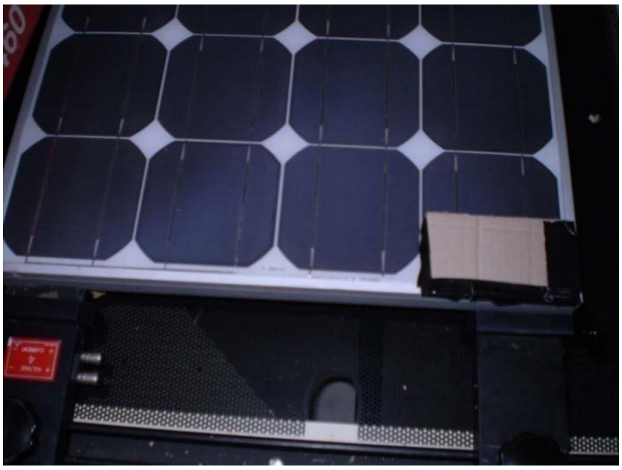

Figure 35 - BP275F Module with Half a Cell Shaded Horizontally

The picture in Figure 35 is a module which has half of a cell horizontally shaded. This is simulated by using cardboard to cover the cell and masking tape to secure the covered cell. The results of the repeated test for the shading scenario in Figure 35 are illustrated in Figure 36 and Figure 37 below.

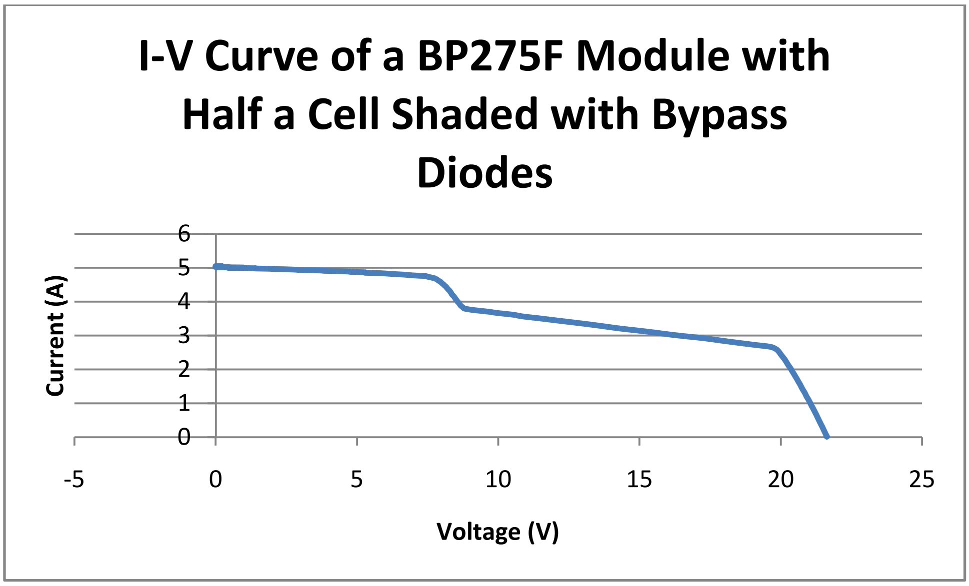

Figure 36 - I-V Curve of a BP275F Module with Half a Cell Shaded Horizontally with Two Bypass Diodes Connected

The output in Figure 36 illustrates the I-V curve of a BP275F module with half a cell shaded with two bypass diodes connected. The BP275F module has 36 cells with 2 bypass diodes connected in parallel with the cells. One bypass diode is connected in parallel with 18 cells. The short circuit current is the same value as that for the unshaded condition. However, at about halfway along the voltage in the x-axis, there is a drop in the current output in the y-axis.

The reason for this output is that the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. However, the dip in the curve at about the halfway point of the I-V curve is a result of the partial shading coming into effect.

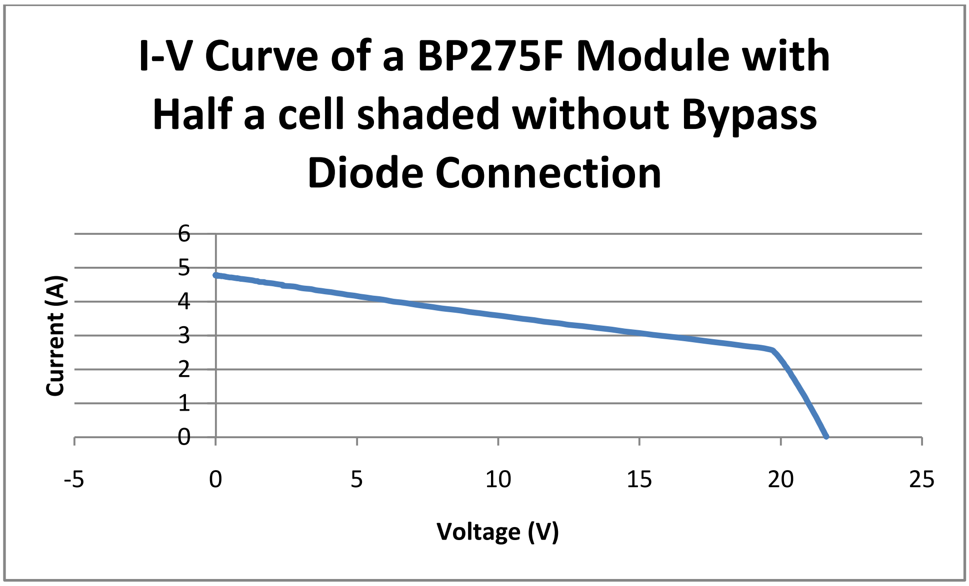

Figure 37 - I-V Curve of a BP275F Module with Half a cell shaded Horizontally without Bypass Diode Connection

The outputted I-V curve in Figure 37 illustrates the output of a BP275F Module without bypass diode connection and with half a cell shaded horizontally. The output expected in Figure 37 is different to that of the actual output because the short circuit current is just below 5A. Whereas, the expected short circuit current for a module with half of a cell shaded without bypass diode connection should be approximately half of the short circuit current for the unshaded condition. This is because the short circuit current of the combined cells should fall to the lowest short circuit current output of the module.

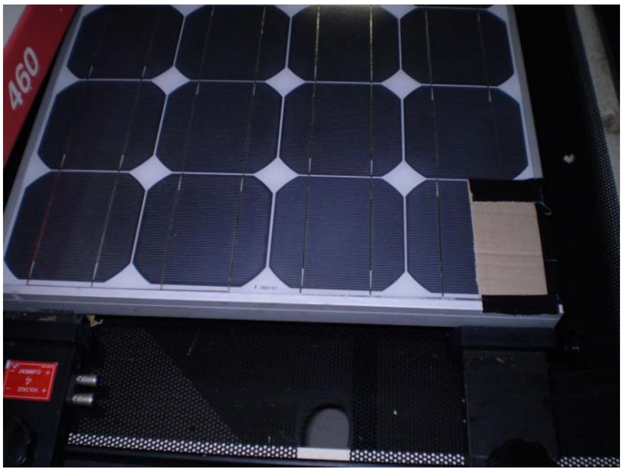

Figure 38 - BP275F Module With Half a Cell Shaded Vertically

The picture in Figure 38 is a module which has half of a cell vertically shaded. This is simulated by using cardboard to cover the cell and masking tape to secure the covered cell. The results of the repeated test for the shading scenario in Figure 38 are illustrated in Figure 39 and Figure 40 below.

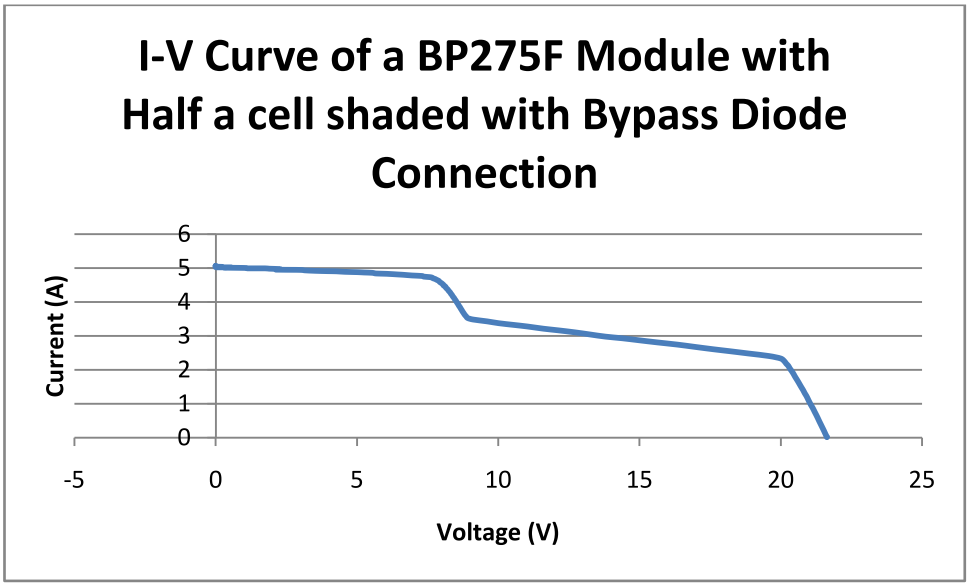

Figure 39 - I-V Curve of a BP275F Module with Half a Cell Shaded Vertically With Two Bypass Diodes Connected

The output in Figure 39 illustrates the I-V curve of a BP275F module with half a cell shaded with two bypass diodes connected. The BP275F module has 36 cells with 2 bypass diodes connected in parallel with the cells. One bypass diode is connected in parallel with 18 cells. The short circuit current is the same value as that for the unshaded condition. However, at about halfway along the voltage in the x-axis, there is a drop in the current output in the y-axis.

The reason for this output is that the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. However, the dip in the curve at about the halfway point of the I-V curve is a result of the partial shading coming into effect.

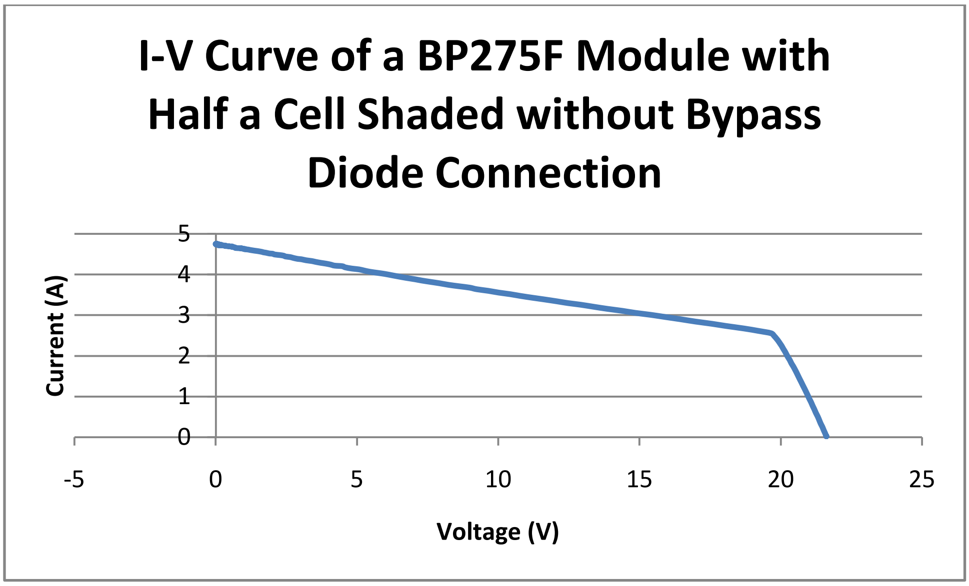

Figure 40 - I-V Curve of a BP275F Module With Half a Cell Shaded Vertically Without Bypass Diode Connection

The outputted I-V curve in Figure 40 illustrates the output of a BP275F Module without bypass diode connection and with half a cell shaded vertically. The output expected in Figure 40 is different to that of the actual output because the short circuit current is just below 5A. Whereas, the expected short circuit current for a module with half of a cell shaded without bypass diode connection should be approximately half of the short circuit current for the unshaded condition. This is because the short circuit current of the combined cells should fall to the lowest short circuit current output of the module.

Figure 41 - BP275F Module with One Cell fully shaded

The picture in Figure 41 is a module which has a cell of a module which is fully shaded. This is simulated by using cardboard to cover the cell and masking tape to secure the covered cell. The results of the repeated test for the shading scenario in Figure 41 are illustrated in Figure 42 and Figure 43 below.

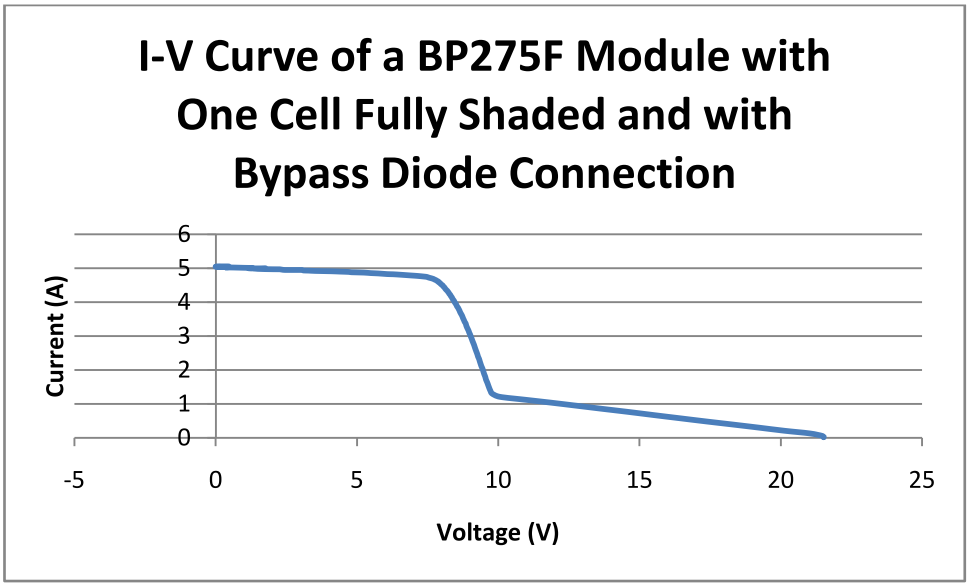

Figure 42 - I-V Curve of a BP275F Module with Bypass Diode Connection and One Cell Fully Shaded

The output in Figure 42 illustrates the I-V curve of a BP275F module with one cell fully shaded and two bypass diodes connected in parallel with the solar cells. The BP275F module has 36 cells with 2 bypass diodes connected in parallel with the cells. One bypass diode is connected in parallel with 18 cells. The short circuit current is the same value as that for the unshaded condition. However, at about halfway along the voltage in the x-axis, there is a more significant drop in the current output in the fully shaded condition than that in the half shaded condition in the y-axis.

The reason for this output is that the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. However, the dip in the curve at about the halfway point of the I-V curve is a result of the partial shading coming into effect.

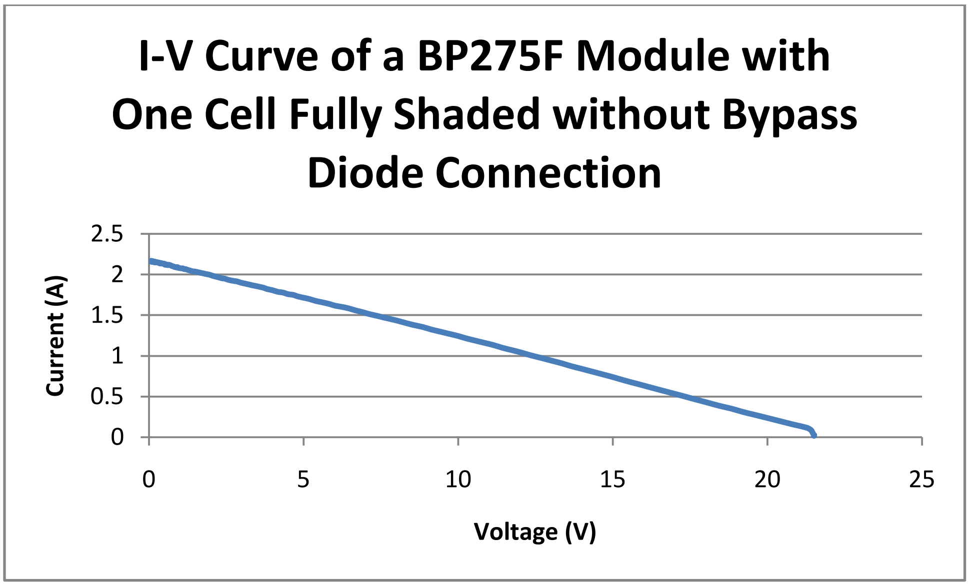

Figure 43 - I-V Curve of a BP275F Module with One Cell Fully Shaded without Bypass Diode Connection

The outputted I-V curve in Figure 43 illustrates the output of a BP275F Module without bypass diode connection and with one cell fully shaded. The output expected in Figure 43 is different to that of the actual output because the short circuit current is just above 2A. Whereas, the expected short circuit current for a module with a cell fully shaded without bypass diode connection should be close to 0A. This is because the short circuit current of the combined cells should fall to the lowest short circuit current output of the module.

For the scenarios with varying degrees of one cell shaded, the results were very similar to the first set of testing conducted on the BP275F module.

However, there were three different conditions tested with two cells shaded at the ROTA compound. These are depicted in the following diagrams with the black rectangle illustrated as the effect of shading as well as being accompanied with the associated photographs and with the corresponding results with and without bypass diode connection:

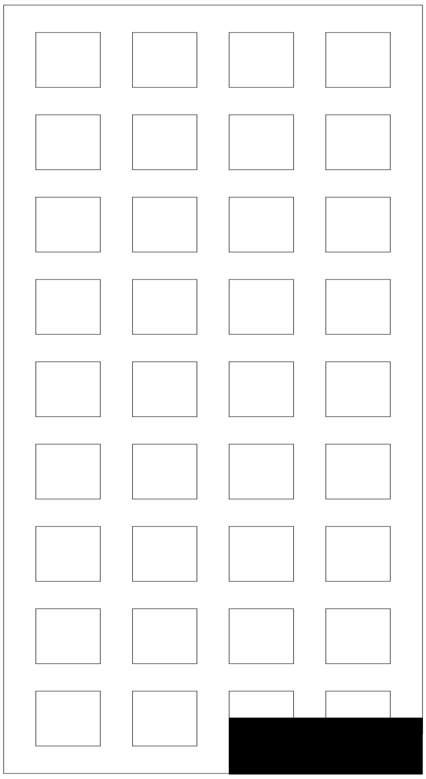

Figure 44 – BP275F Module With Two Cells at the front of the Tray and the Left Corner Half Shaded

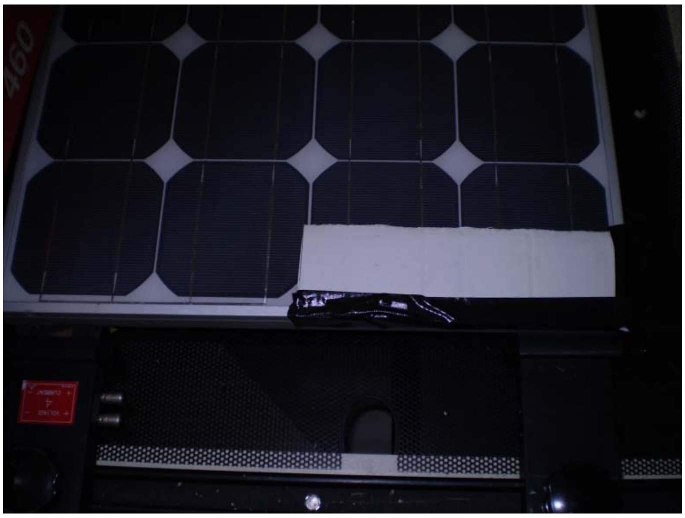

Figure 45 - BP275F Module With Two Cells at the Front of the Tray and the Left Corner Half Shaded

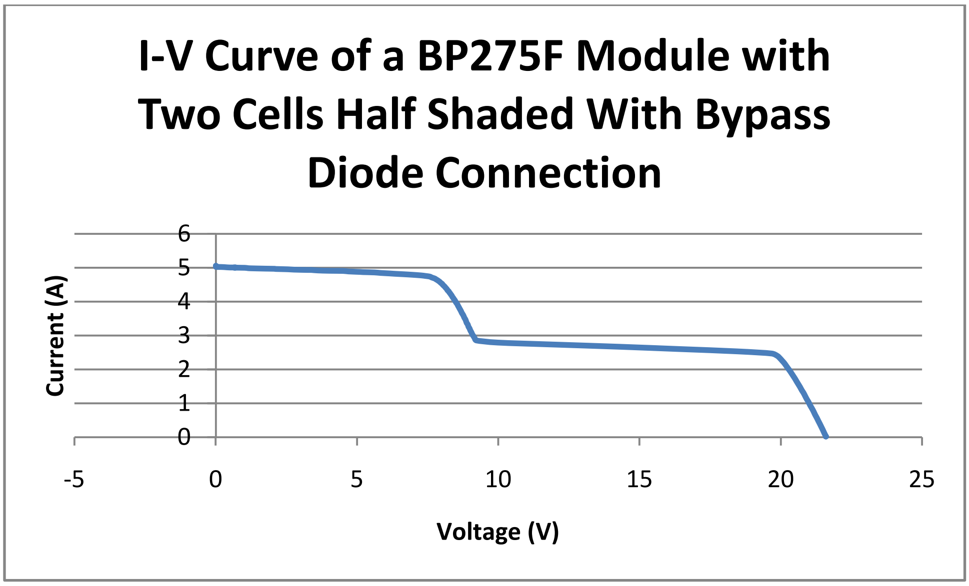

Figure 46 - I-V Curve of a BP275F Module with Two Cells at the Front of the Tray and the Left Corner Half Shaded With Bypass Diode Connection

The graph in Figure 46 illustrates the I-V curve output of a BP275F Module with two cells at the front of the tray and at the left corner half shaded. The short circuit current is the same as that for the unshaded condition. The reason for that is because the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. At approximately, halfway along the x-axis, the current output decreases to just under 3A due to the half shading across two of the cells.

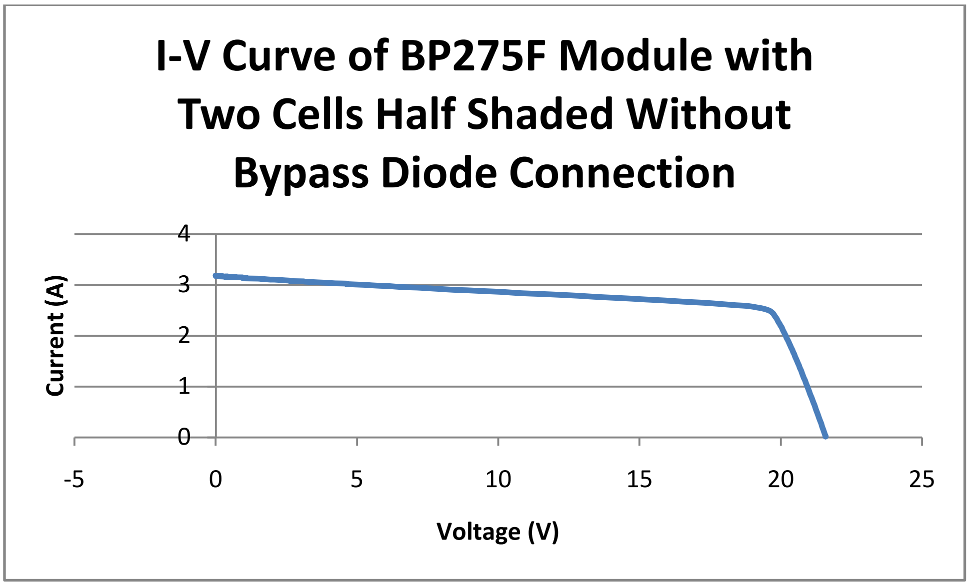

Figure 47 - I-V Curve of a BP275F Module with Two Cells at the Front of the Tray and the Left Corner Half Shaded Without Bypass Diode Connection

The graph in Figure 47 illustrates the I-V curve output of a BP275F Module with two cells at the front of the tray and at the left corner half shaded. The short circuit current is reduced to just over 3A due to the half shading across two of the cells and the combined current output of the BP275F module falls to the lowest short circuit current output of a cell within the module.

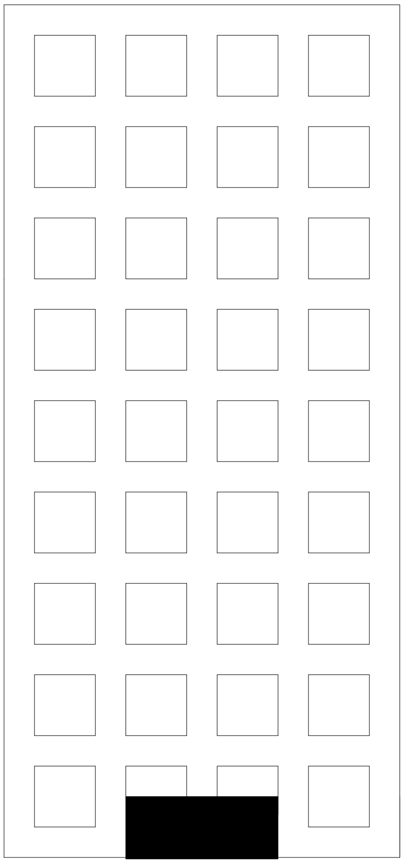

Figure 48 – BP275F Module with the Two Central Cells at the Left Corner Half Shaded

Figure 49 - BP275F Module with the Two Central Cells at the Left Corner half shaded

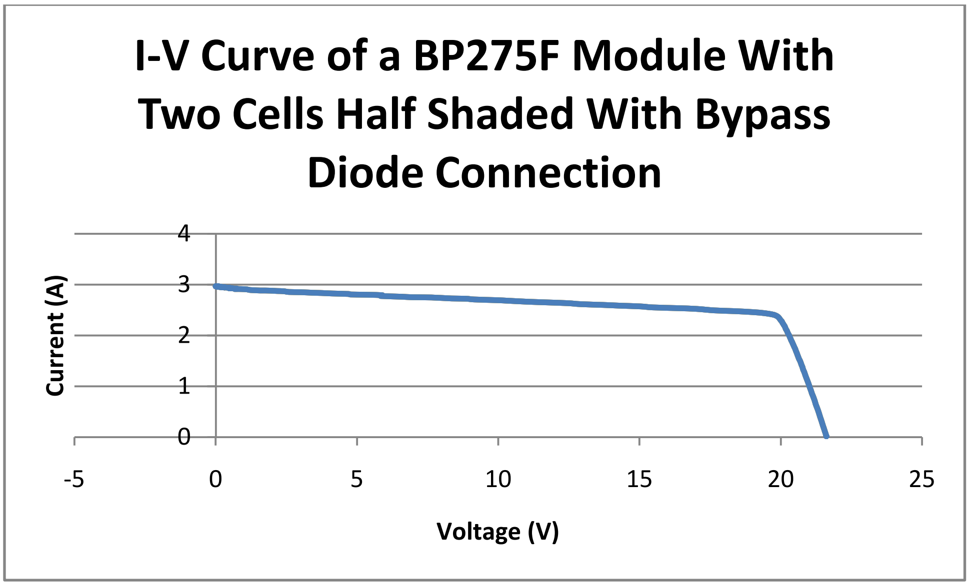

Figure 50 - I-V Curve of a BP275F Module with the Two Central Cells at the Left Corner Half Shaded With Bypass Diode Connection

The graph in Figure 50 illustrates the I-V curve output of a BP275F Module with two cells at the centre of the tray and at the left corner half shaded. The short circuit current is reduced to about 3A. The short circuit current output is less for the half shaded condition of two cells than that for the unshaded condition. The reason for that is because one cell out of 18 cells connected in parallel across one bypass diode is half shaded.

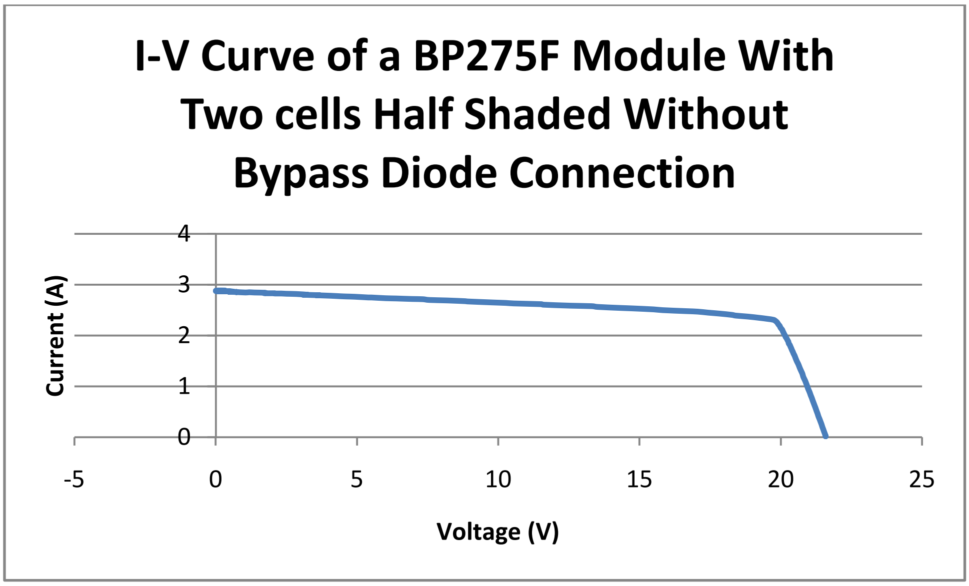

Figure 51 I-V Curve of a BP275F Module with the Two Central Cells at the Left Corner Half Shaded and without Bypass Diode Connection

The graph in Figure 51 illustrates the I-V curve output of a BP275F Module with two cells at the centre of the tray and at the left corner half shaded. The short circuit current is reduced to about 3A. The short circuit current output is less for the half shaded condition of two cells than that for the unshaded condition. The short circuit current is reduced to just under 3A due to the half shading across two of the cells and the combined current output of the BP275F module falls to the lowest short circuit current output of a cell within the module.

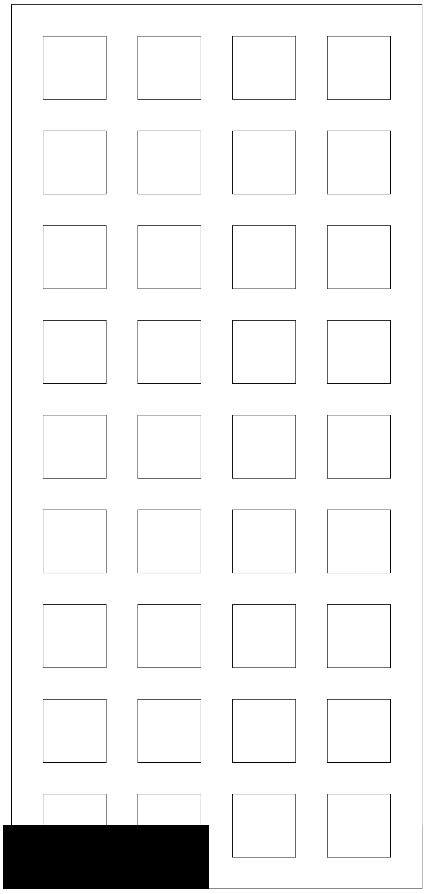

Figure 52 – BP275F Module With the Two Back Cells at the Left Corner Half Shaded

Figure 53 - BP275F Module With the Two Back Cells at the Left Corner Half Shaded

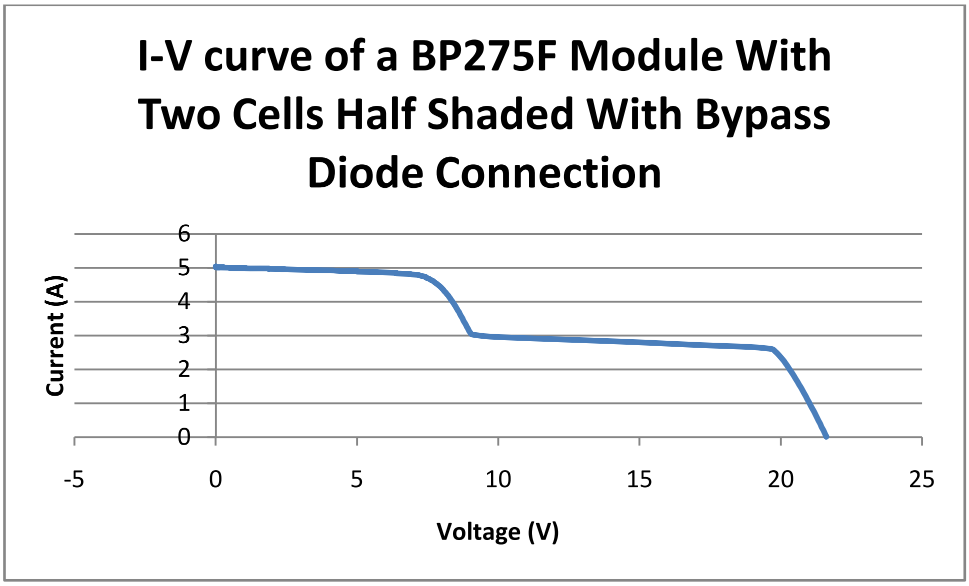

Figure 54 I -V Curve of a BP275F Module with the Two Back Cells at the Left Corner Half Shaded and With Bypass Diode Connection

The graph in Figure 54 illustrates the I-V curve output of a BP275F Module with two cells at the front of the tray and at the left corner half shaded. The short circuit current is the same as that for the unshaded condition. The reason for that is because the bypass diode ensures that the full current flows through at least the 18 non-shaded cells. At approximately, halfway along the x-axis, the current output decreases to about 3A due to the half shading across two of the cells.

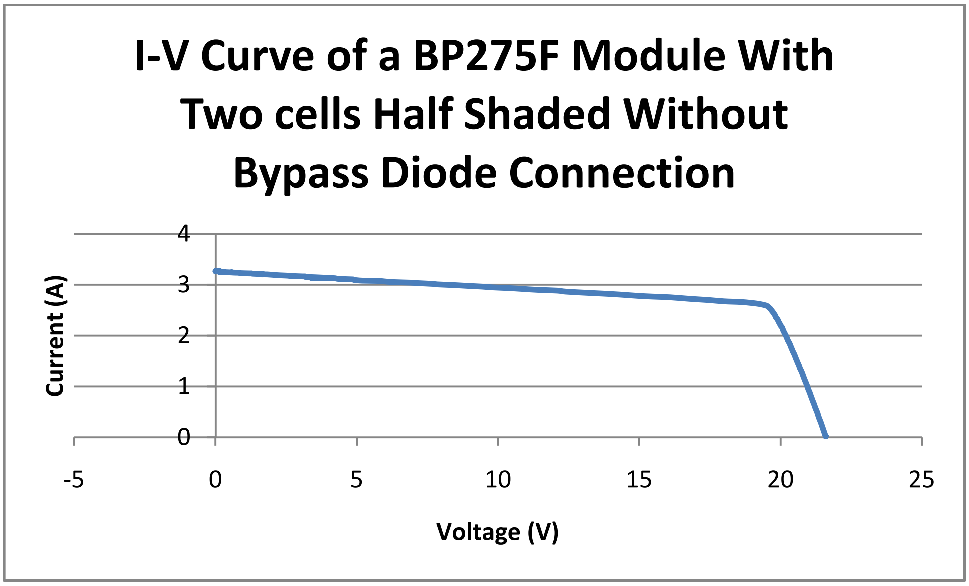

Figure 55 I-V Curve of a BP275F Module With the Two Back Cells at the Left Corner Half Shaded and Without Bypass Diode Connection

The graph in Figure 55 illustrates the I-V curve output of a BP275F Module with two cells at the front of the tray and at the left corner half shaded. The short circuit current is reduced to just over 3A due to the half shading across two of the cells and the combined current output of the BP275F module falls to the lowest short circuit current output of a cell within the module.

The results illustrated with the effects of shading and mismatch with the different positions of the two half shaded cells are interesting in that the results correlating to the two shaded central cells at the left corner are quite different to that of those with the back two shaded cells and the front two shaded cells.

Appendix D: The CD Contents

1.) Electronic Copy of this Report

2.) ICAP Model of a Module with Bypass Diode Connection

3.) ICAP Model of a Module without Bypass Diode Connection

4.) Microsoft Excel Curve Fitting Spreadsheet

5.) Project Presentation

Glossary:

Activation Energy – This is denoted by the symbol (Eg) and is defined as the minimum amount of energy required to initiate a particular process. In the context of semi-conductor device reliability, this refers to the minimum amount of energy required to trigger a temperature accelerated failure mechanism. (16)

Breakdown Voltage - The voltage measured at a specified current in the electrical breakdown region of a semiconductor diode. (17)

Bypass Diode – A diode connected across one or more solar cells in a photovoltaic module such that the diode will conduct if the cell/s become reverse biased. It protects these solar cells from thermal destruction in case of total or partial shading, broken cells, or cell string failures of individual solar cells while other cells are exposed to full light. (10)

Emission Co-efficient - This is the diode emission co-efficient or ideality factor. This is dependent on the material and physical construction of diodes. (20)

Flicker Noise – This is a type of electronic noise with a 1/f or pink spectrum.

Grading Co-efficient - is related to the doping profile of the junction. (21)

ICAP/4 – This is Intusoft's fourth generation analog and mixed signal circuit simulation package and is used in electronic design automation. The ICAP/4 tools utilise SpiceNet as the schematic and design management system. (8)

Mismatch - When the PV cells connected within a PV array do not have the same characteristics.

Module – A typical module has a connection of 36 cells with 2 bypass diodes connected in parallel across the 36 cells.

Ohmic Resistance – This is the series diode connection resistance. (9)

Open-Circuit Voltage – The open-circuit voltage (Voc) is the maximum voltage across a device and occurs when the current from a solar cell is zero.

Parameter Measurement Temperature – This is the nominal temperature at which the temperature dependence of the saturation current is measured at. (6)

PVSim – A windows based program which is used to analyse individual cells, to analyse the effects of cell mismatch or reverse bias ("hot spot") heating in modules, and to analyse the performance of large arrays of modules including bypass and blocking diodes. (5)

Reverse Breakdown Voltage - Amount of reverse bias that will cause a PN junction to break down and conduct in the reverse direction. (18)

Saturation Current – This is the maximum current which can be obtained under certain conditions. In a semiconductor, this is the maximum current which just precedes a change in conduction mode. (22)

Shading – A shadow of a surrounding object which is cast over a PV array.

Short-Circuit Current – The short-circuit current (Isc) is the maximum current from a solar cell and occurs when the voltage across the device is zero.

Simulink – Is an environment for multi-domain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing. Simulink is also integrated with Matlab, providing immediate access to an extensive range of tools that let you develop algorithms, analyse and visualize simulations, create batch processing scripts, customize the modelling environment, and define signal, parameter, and test data. (9)

Solar Cells – Are p-n junction diodes of large area whose properties are optimised for the absorption of sunlight and the collection of the resulting photo-electrons and holes. (23)

Spice - is a general-purpose circuit simulation program for nonlinear dc, nonlinear transient, and linear ac analyses. Circuits may contain resistors, capacitors, inductors, mutual inductors, independent voltage and current sources, four types of dependent sources, lossless and lossy transmission lines (two separate implementations), switches, uniform distributed RC lines, and the five most common semiconductor devices: diodes, BJTs, JFETs, MESFETs, and MOSFETs. (10)

Transit Time – This is the parameter which defines the electron lifetime, hole lifetime or a combination of the two. (19)