Simulation of the effects of global irradiance, ambient temperature and partial shading on the output of the photovoltaic module using MATLAB/Simulink and ICAP/4

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Engineering Thesis Project

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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.

.................Evgeniya Polyanskaya................22/01/2013..........

Acknowledgements:

I would like to thank my supervisor Greg Crebbin for guiding and suggesting the ideas to work on.

I would like to thank my family for giving me the support needed while I was working on the thesis.

Also I would like to thank my friends who gave me the support and all the space I needed during this semester.

Abstract

This thesis is investigates the effects of operating conditions on the output of a photovoltaic module and describes methods used for maximising the power output of the module.

A photovoltaic (PV) cell was simulated using MATLAB/Simulink software at different ambient temperatures and the output power of the cell was recorded. Global irradiance and its effect on the power output of the cell were also simulated. The effect of partial shading on the output power of a module was simulated using ICAP/4 software.

Simulations showed that the output power of a photovoltaic cell decreased as the amount of global irradiance was decreased. Array positioning and physical solar tracking were described as methods of maximising the amount of global irradiance a module receives.

Results of the simulations showed that high ambient temperatures cause the output power of a photovoltaic cell to decrease. Elevation of a module above the ground and having enough space around the module are proposed as methods that can be used to keep the temperature of photovoltaic cells down, thereby increasing the efficiency and the power produced.

Different cases of partial shading were simulated. Bypass diodes were introduced and investigated as a method for decreasing the effects of partial shading on the output power of a module. Blocking diodes were described as a way to stop the module from discharging the battery when a module does not receive any solar irradiation.

A Maximum Power Point Tracker was described as another way of maximising power output of the module.

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Table of Symbols

Symbol	Description
Ω	Ohm
A	Ampere
C	Celsius
Eg	Bandgap for semiconductor material (Eg(Si) =1.1 eV)
I	Output current of a cell (A)
Id	Current through the diode (A)
Ior	Inverse diode saturation current (A)
Iph	Photocurrent (A)
Ir	Global solar irradiance (W/m^2)
Iro	Irradiance under Standard Test Conditions (1000 W/m^2)
Is	Inverse saturation current of the pn junction (A)
Isc	Short-circuit current (A)
Ish	Current through the shunt resistance (A)
It	Short-circuit current temperature coefficient (A/^{0}K)
J	Joules
K	Kelvin
k	Botzmann's constant (1.38 x 10^{-23} J/^{0}K)
MPP	Maximum Power Point
MPPT	Maximum power Point Tracker
m	metre
n	Emission coefficient
NOCT	Normal operating temperature (^{0}C)
q	Electron charge constant (1.602 x 10^{-19}Coulombs)
Rs	Series resistance (Ω)
Rsh	Shunt resistance (Ω)
Ta	Ambient temperature (^{0}C)
Tc	Cell temperature in (^{0}C)
Tref	Reference temperature (K)
V	Voltage (or Volts as a unit)
W	Watts

Introduction

Using the photovoltaic effect to produce power was first exercised as far back as the 19th Century *(Solar panel brief history and overview)*. There has been a lot of development in photovoltaic cells and different types of cells have been created and utilised. The efficiency of the photovoltaic cells has increased since then.

Using photovoltaic modules as a power source has a lot of advantages. Some of the advantages are their minimal impact on the environment, low maintenance, long lifetime and the fact that there is no need for fuel, unless a generator is connected as a part of a stand-alone system.

Even though there have been a lot of developments relevant to photovoltaic cells and there are a lot of advantages in using them to provide power, it is still expensive to make photovoltaic cells. High production costs of photovoltaic cells reflect on the capital cost of a module or an array.

Photovoltaic modules have a low efficiency compared to some other renewable energy sources. Therefore it is important for the power output of the modules to be maximised.

This thesis is focused on simulating a photovoltaic cell and a module in different operating conditions and methods used to maximise the power output under those conditions.

During the simulations the ambient temperature and the global irradiance were varied using MATLAB/Simulink software (*Simulink*). The effect of partial shading on the output power of the modules was simulated using ICAP/4 (*ICAP/4*) software.

The work described in this thesis would be useful for future researcher who is interested in modelling the photovoltaic modules in MATLAB/Simulink or ICAP/4. The models used in this thesis can be used by future researcher to get familiar with the operation of a cell or a module under different operating conditions.

Chapter 1 Background information

1.1 Model of a single photovoltaic cell

A photovoltaic module consists of a number of photovoltaic cells connected in a particular configuration.

It is important to understand the components and the operation of a single photovoltaic cell, then the operation of the module under different conditions is easier to understand.

An ideal photovoltaic cell consists of a current source and a diode. A non-ideal model of a photovoltaic cell has an additional shunt resistance connected parallel to the diode and a series resistance. An equivalent circuit of a photovoltaic cell is shown in Figure 1.1.
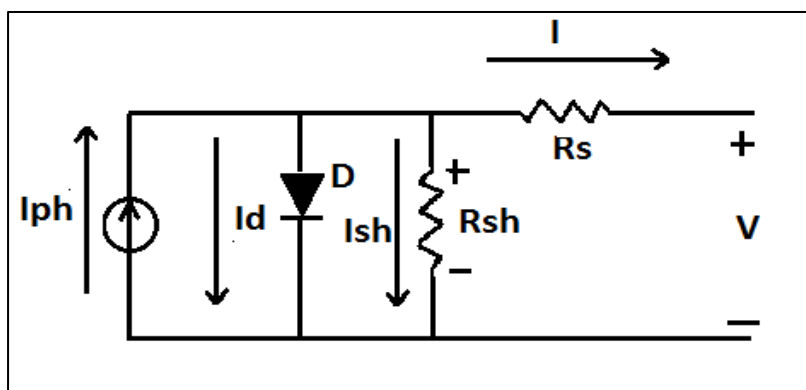
Figure 1.1 Equivalent circuit of a photovoltaic cell

The light generated current is modelled as a current source, as shown in Figure 1.1. The light generated current depends on the amount of irradiation the cell receives.

The output current of the cell is thus calculated by the equation (Ramos-Hernanz et al. 2012, 47):

$I = Iph - Id - Ish$ equation (1)

where I is the output current of a cell (A),

Iph is the photocurrent (A),

Id is the current through the diode (A),

Ish is the current through the shunt resistance (A).

The output current of a photovoltaic cell can be plotted against the output voltage. This plot shows the relationship between the output current and the voltage at the terminals of the cell. Usually this plot is called an I-V plot or an I-V characteristic (*Current-voltage characteristic*).

1.2 I-V characteristic of a cell

When a photovoltaic cell does not have a current going through it, the voltage across the cell is an open circuit voltage (*Open-Circuit Voltage*). The open-circuit voltage is the maximum voltage across a solar cell and it is shown in Figure 1.2 as Voc.

Figure 1.2 shows the I-V characteristic and the power plot of a photovoltaic cell.
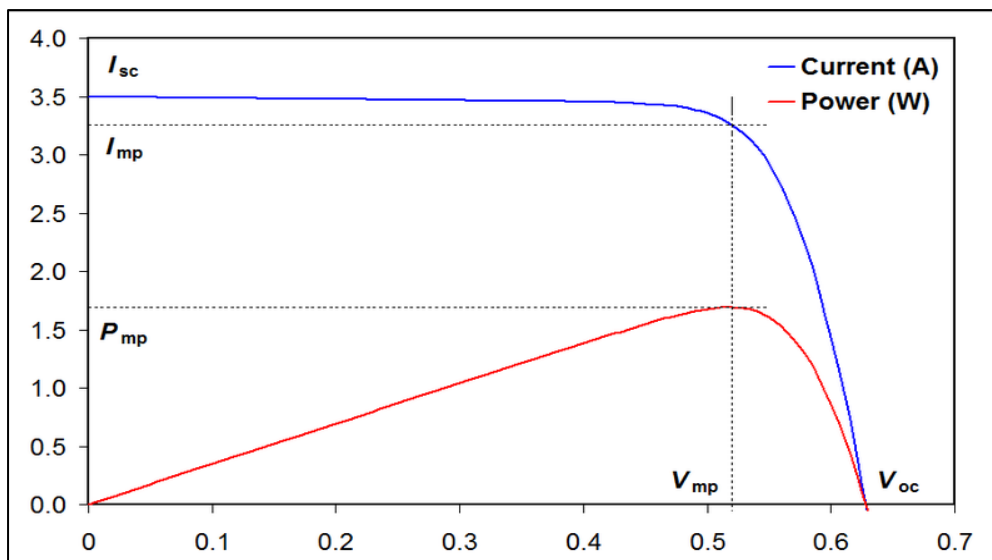
Figure 1.2 The I-V characteristic and the power plot of a photovoltaic cell (*I-V_Curve_MPP*)

When the voltage across the photovoltaic cell is equal to zero, the output current of the cell is the short-circuit current (Tiwari and Dubey 2010, 97). The short-circuit current is the maximum output current of the cell. It is shown in Figure 1.2 as Isc.

It is desirable for a cell to provide the maximum output power. The maximum power is generated by the cell if it is operating at its maximum power point.

The maximum power point is the point on the I-V curve of a cell where the product of the corresponding current and the corresponding voltage is a maximum (*Glossary of*

Solar Energy Terms). The cell voltage at the maximum power point is shown in Figure 1.2 as Vmp. The current at the maximum power point is shown in Figure 1.2 as Imp.

Global irradiance and ambient temperature affects the shape of the I-V characteristic (Ha¨berlin 2012), thereby affecting the maximum power point and the maximum power that could be delivered by the cell. Shading also has an influence on the shape of the I-V curve.

1.3 Effect of global radiance on the power output of a cell

"Irradiance is the power of the electromagnetic radiation per unit area incident on the surface" (*Irradiance*).

Global irradiance is the sum of the direct and the diffuse irradiances. Global irradiance of the tilted object also consists of irradiance reflected from the ground (*Irradiance*).

The output current of a cell is directly proportional to global irradiance (Tiwari and Dubey 2010, 111).

Figure 1.3 shows the I-V characteristic of the cell under varied irradiance conditions.
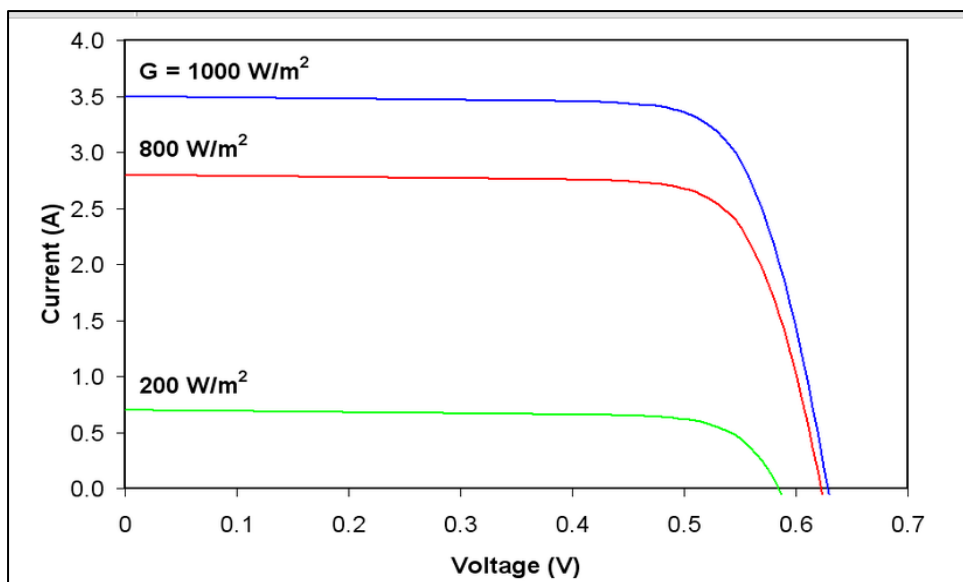
Figure 1.3 Effect of irradiance on the I-V plot (*I-V_Curve_G)*

When the global irradiance increases the output current of the cell also increases, while the open-circuit voltage of a cell increases only slightly (Ha¨berlin 2012). When the irradiance is increased, the maximum output power of a cell also increases.

In this thesis PV cells are modelled in MATLAB/Simulink under different irradiance conditions.

The level of global irradiance falling on the module should be maximised, so that the module generates maximum power. Some methods used to maximise the level of global irradiance falling on the module will be suggested in Chapter 2.

1.4 Effect of ambient temperature on the output of the photovoltaic cell

Ambient temperature of the photovoltaic cell is the temperature surrounding the cell.

Figure 1.4 shows the I-V characteristic of a photovoltaic cell under varied temperature conditions

When the ambient temperature is increased, the output current of the cell slightly increases, while the open-circuit voltage decreases (Ha¨berlin 2012) as shown in Figure 1.4.

The efficiency and the power output of the cell decrease with increasing ambient temperature (Reddy 2010, 92).
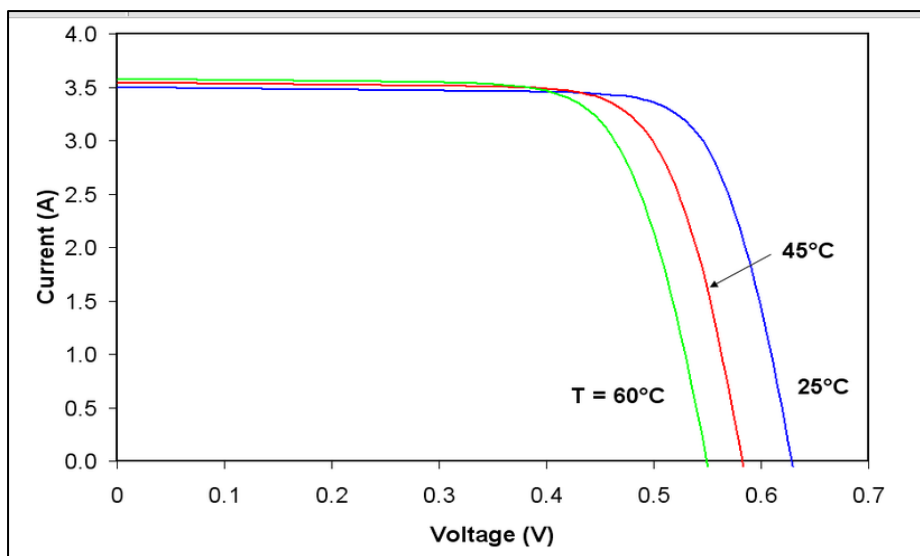
Figure 1.4 Effect of temperature on the I-V characteristic of a photovoltaic cell (*I-V_Curve_T*)

In this research a photovoltaic cell will be simulated in MATLAB/Simulink at 5^0C, $25\ ^0$C and 45^0C to show that the increased ambient temperature decreases the maximum power output of the cell.

The ambient temperature and the temperature of the photovoltaic cells should be kept low. For a photovoltaic cell, installation of the module with space around it to keep the cell temperature down is desirable.

1.5 Partial shading of the module

Partial shading of a module decreases the output power of a module.

When a cell in the module is fully shaded, it starts to operate in the reverse bias region, consuming power instead of generating power. A single cell operating in the reverse bias region could cause enough power dissipation to damage the cell (Tiwari and Dubey 2010, 123-125). Partial shading of a module with and without bypass diodes was simulated in ICAP/4.

Bypass diodes are used to decrease the effect of partial shading on the power output of a module. Partial shading of a module with bypass diodes was simulated in ICAP/4.

Before installation of a module, the chances of shading by near-by objects should be eliminated whenever possible. If the chance of the module being shaded is high then a different location for the module should be considered.

1.6 Maximum Power Point Tracker

A Maximum Power Point Tracker is used in photovoltaic systems for maximising the power output.

A Maximum Power Point Tracker usually consists of a Controller, Pulse Width Modulation Unit and a DC/DC converter (Castaner, Luis, and Silvestre 2002, 147).

The controller reads the output current and the operating voltage of the module. Based on that information, the controller uses Pulse Width Modulation and a DC/DC converter to adjust the voltage of the module. When a change is detected the voltage of the module is adjusted so that the module operates at its maximum power point. (Gules et al. 2008)

Maximum Power Point Trackers are also used to limit the output power of the module when the load is low and the battery is charged.

DC/DC converters and controller methods are described in more detail in Chapter 5.

1.7 Programs used

Computer Programs that were considered for simulations for this thesis were MATLAB/Simulink and ICAP/4, PSPICE (*PSPICE 9.1 student version*) and Power Factory (*PowerFactory*).

MATLAB/Simulink was used to simulate a single photovoltaic cell at different irradiance levels. This model did not account for an effect of the ambient temperature on the output power of the cell.

Then MATLAB/Simulink was used to simulate an improved model of the single photovoltaic cell at different ambient temperatures. Simulations of the photovoltaic cells in MATLAB/Simulink were based on the equations. The data from simulations was saved and plotted using Excel.

A photovoltaic module was simulated in ICAP/4 to show the effect of partial shading on the power output of the module. The data from ICAP/4 simulations was saved and plotted using Excel.

PSPICE was used to get familiar with the simulation of the circuits. PSPICE was initially considered for simulation of the partial shading of the module, but in the end ICAP/4 was chosen. ICAP/4 also has an option of simulation based on the equations.

Modelling of the cell in Power Factory was also looked into. Power Factory could be also used for modelling of a cell based on the equation described in this thesis.

Chapter 2 Simulation of a PV cell at different levels of global radiation using MATLAB/Simulink

2.1 Simulation model

A single photovoltaic cell was simulated in MATLAB/Simulink. The cell was simulated to get familiar with the equations used in the calculation of the output power.

The simulation process in this thesis was based on the work of Ramos-Hernanz et al. (2012, 45-47), that included a simulation of a PV cell in MATLAB/Simulink under varying irradiance conditions. However, the simulation created by Ramos-Hernanz *et al., op. cit., p 45-47,* did not account for changes in the ambient temperature.

The model was adjusted and it is now accounting for effects of ambient temperature on the output power of a cell. Equations used in this simulation were based on those described in "*Control of Photovoltaic-Diesel Hybrid Energy Systems*" (Wichert 2000). Those equations are attached in Appendix A.

A window of the simulation used in this chapter is shown in Figure 2.1. The simulation model was named PV Cell and is attached as an electronic copy in Appendix B.
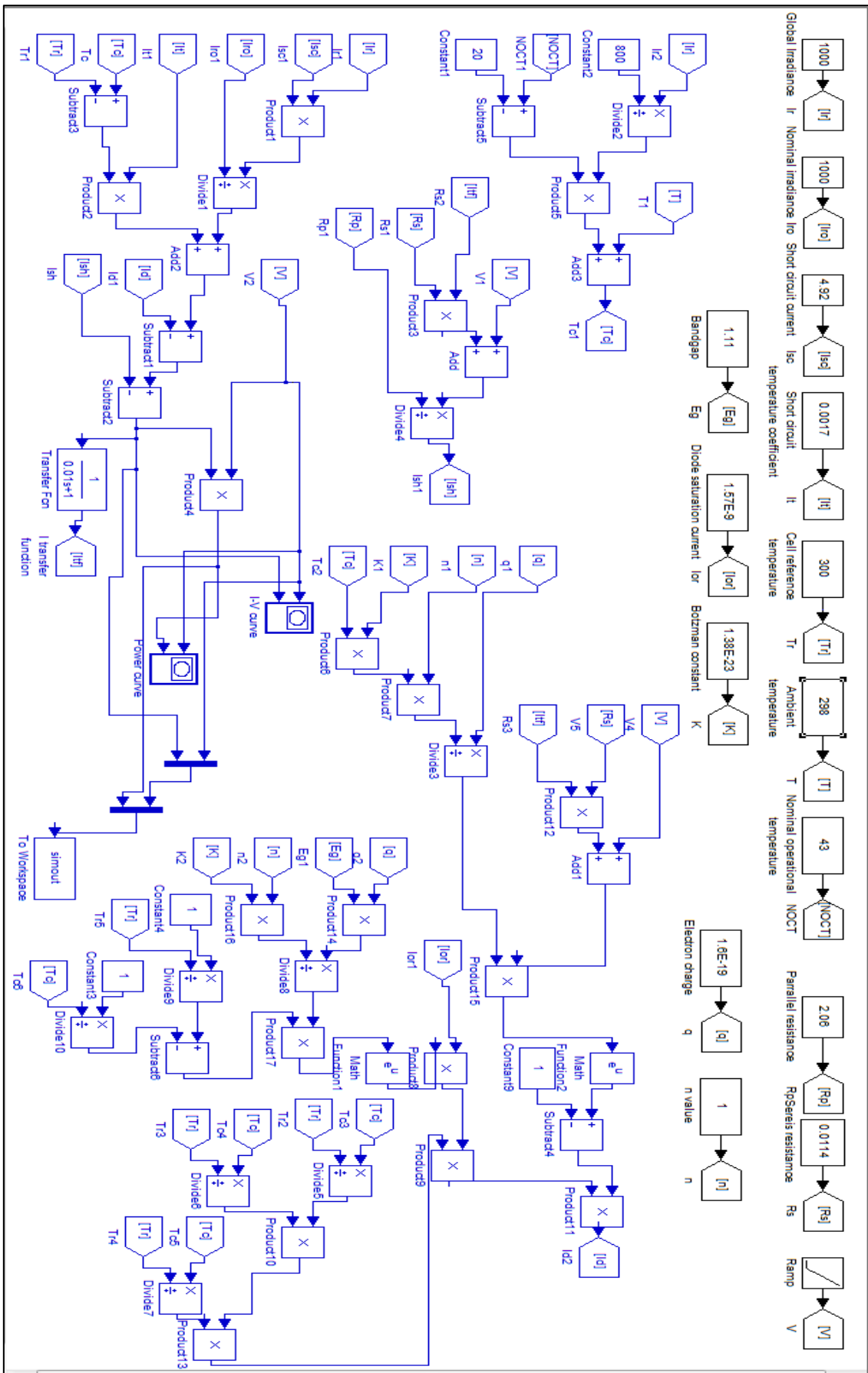
Figure 2.1 PV Cell model in MATLAB/Simulink

The simulation was based on the calculation of a diode current *Id*, a photocurrent *Iph* and a current going through the shunt resistances of the cell *Is*. Then the output current of a cell was calculated from the equation (1), which is repeated here:

I=Iph-Id-Ish   equation (1)

Other equations used in this MATLAB/Simulink model are described in Appendix A.

This simulation was useful for displaying and recording the output current and output voltage of the cell under different irradiance conditions. However, it is limited to calculation of the output of only a single cell.

2.2 Inputs

The first two rows in the simulation window of PV Cell are inputs as shown in Figure 2.1. The inputs include the ambient temperature, nominal operational temperature, short circuit current, series resistance, shunt resistance, nominal irradiance, global irradiance, electron charge constant, emission coefficient, Boltzmann's constant, short circuit temperature coefficient, cell reference temperature and diode saturation current.

The data from "An Icap/4 Simulation Model of a Photovoltaic Module" (Thompson 2010) was used as inputs for the simulation of a module under different irradiance conditions in MATLAB/Simulink. As a part of her thesis Thompson, *op. cit.,* ran tests with a photovoltaic module using the Sun Simulator at Murdoch University. The data recorded during the experiments was used to calculate the parameters of the photovoltaic model used.

Thompson, *op. cit.,* used a photovoltaic module that had 36 cells connected in series. The short circuit current of each cell was calculated to be 4.92 Amperes. The shunt resistance of the cell was calculated by Thompson, *op. cit.,* to be 2.06 Ohms and the series resistance was calculated to be 0.0114 Ohms. The diode's saturation current was calculated to be 1.52×10^{-9} Amperes and the emission coefficient was equal to 1.

This data was used for all the simulations in this thesis using MATLAB/Simulink and ICAP/4 softwares, as shown in Figure 2.2.

Inputs	
Short circuit current (A)	4.92
Shunt resistance (Ω)	2.06
Series resistance (Ω)	0.0114
Diode's saturation current (A)	1.52 x 10E-9
Emission coefficient	1
Short circuit temperature coefficient (A/^{0}K)	1.7×10^{-3}
Cell reference temperature (^{0}K)	300
Normal operating cell temperature (^{0}C)	43

Figure 2.2 Inputs of the MATLAB/Simulink model

The PV Cell model needed inputs for a short circuit temperature coefficient, a cell reference temperature and a normal operating cell temperature. Those values were taken from Wichert's thesis, *op. cit.* The short circuit temperature coefficient used was 1.7×10^{-3} A/^{0}K. The cell reference temperature used in the simulations was 300^0K. The normal operating cell temperature used was 43^0C.

The irradiance was varied using MATLAB/Simulink software from 1000 W/m^2 down to 750 W/m^2, then down to 500 W/m^2 and finally to 250 W/m^2. A single cell was modelled in MATLAB/Simulink and the output current and the output power of the cell under those conditions were saved to Excel and plotted. Plots of those results are shown in Figure 2.3, Figure 2.4 and Figure 2.5.

2.3 Results
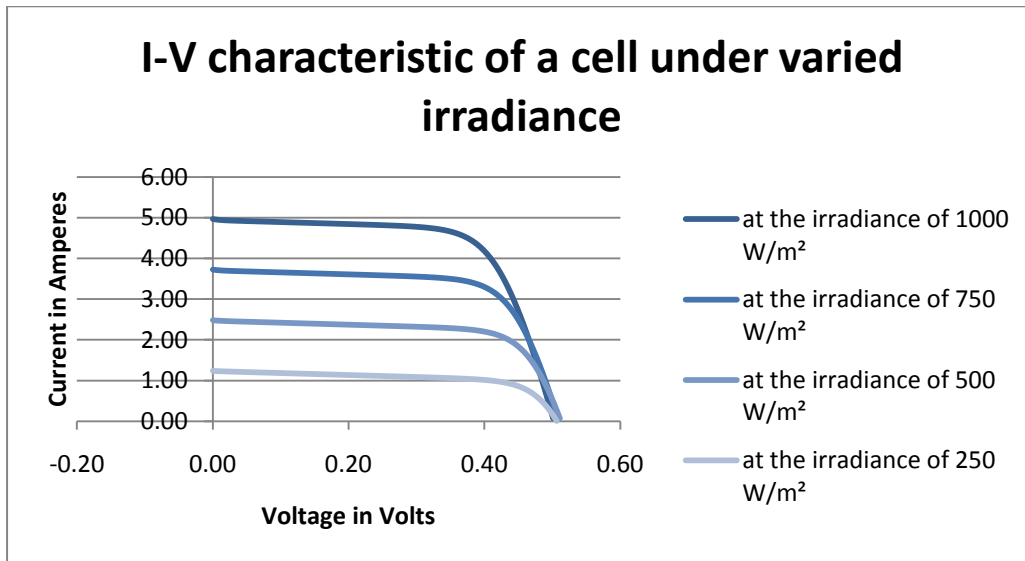
Figure 2.3 I-V characteristic of a cell under varied irradiance
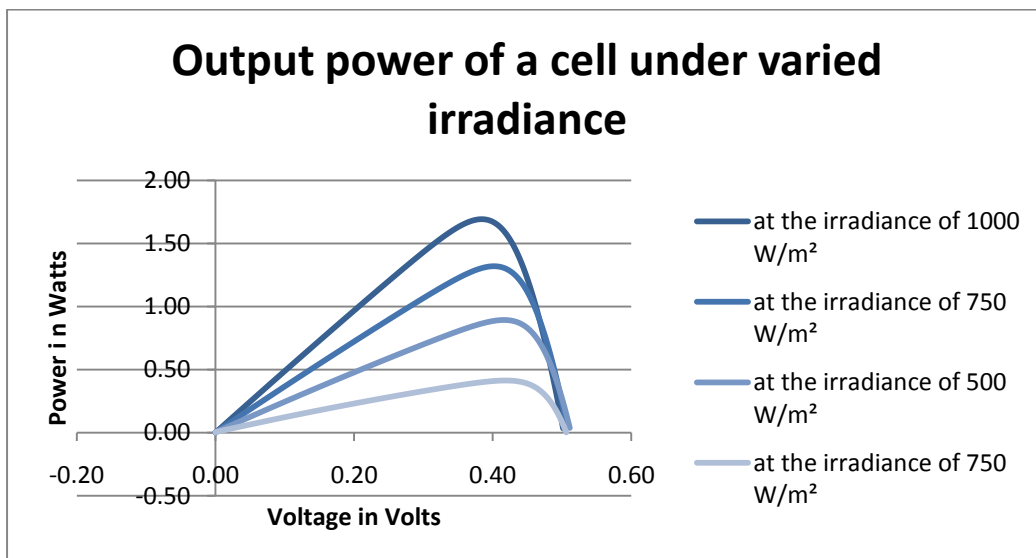
Figure 2.4 Output power of a cell under varied irradiance

Maximum Power Points of a cell under varied irradiance			
Irradiance (W/m²)	Power at MPP (Watts)	Current at MPP (Amperes)	Voltage at MPP (Volts)
1000	1.69	4.38	0.39
750	1.32	3.29	0.4
500	0.89	2.13	0.42
250	0.41	0.97	0.42

Figure 2.5 Maximum power points of a cell under varied irradiance

2.4 Interpretation of the results

From Figure 2.4 and Figure 2.5 the maximum output power of a cell at irradiance of 1000 W/m² was equal to 1.69 Watts. The cell would produce this maximum output power at the output voltage of 0.39 Volts and at the output current of 4.38 Amperes as shown in Figure 2.3.

As the irradiance level was decreased from 1000 W/m² to 750 W/m², the maximum output power decreased from 1.69 Watts down to 1.32 Watts as showing in Figure 2.4. The cell would produce this maximum output power at the output voltage of 0.40 Volts and at the output current of 3.29 Amperes.

As the irradiance level was decreased from 750 W/m² to 500 W/m², the maximum output power has decreased from 1.32 Watts down to 0.89 Watts. The cell would produce this maximum output power at the output voltage of 0.42 Volts and at the output current of 2.13 Amperes.

As the irradiance level was decreased from 500 W/m² to 250 W/m², the maximum output power has decreased from 0.89 Watts to 0.41 Watts. The cell would produce this maximum output power at the output voltage of 0.42 Volts and at the output current of 0.97 Amperes as shown in Figure 2.5.

From results of this simulation as the irradiation level was decreased the output power of a cell decreased. Therefore to keep the output power of a module at maximum the irradiance level received by the module should be maximised.

2.5 Maximising the amount of irradiance falling on the module

Some methods used to maximise the amount of global irradiance are described in this section.

2.5.1 Array position

The sun changes its position in the sky over the course of the day. Furthermore, the trajectory of the sun in the sky changes with seasons. The sun appears lower in the sky during the winter months.

An array of modules should be tilted at an angle in order to maximise yield, sometimes optimising the yield for a specific season. Tilt angle is usually close to latitude angle of the installation site (*Solar Photovoltaic Power System Handbook*). The array of modules should be installed facing the equator (*Optimum tilt of solar panels).*

2.5.2 Solar tracking

There is an option of having a mobile base for an array, which will tilt the module and place it facing the sun.

Solar tracking increases the amount of solar irradiation falling on the module during the day. Also solar tracking helps to increase the amount of solar irradiation falling on the module during winter months when the sun is lower in the sky.

The module could be moved along a single or double axis (*Dual-Axis tracking generates more power*). Single axis movement will allow the module to tilt along one plane. Double-axis allows the module to rotate along horizontal and vertical planes, improving flexibility of the array.

Solar tracking maximises the power output of the module. However, adding solar tracking to the system increases the capital cost and the maintenance of an array, which should be considered before the installation. This paper does not address the issue of power gain from constant tracking versus power loss in driving the mechanical tracking system.

2.6 Conclusion

MATLAB/Simulink model was useful to demonstrate the dependence of the output power of the module on the global irradiance. The amount of irradiance falling on the module should be maximised. That could be done by tilting the modules at the latitude angle of the installation place or by the module being able to tilt towards the sun.

Chapter 3 Simulation of a PV cell under different ambient temperatures conditions using MATLAB/Simulink

3.1 Simulation model

The photovoltaic model used for this simulation is the same MATLAB/Simulink model that was described in Chapter 2.

In Chapter 2 a photovoltaic cell was simulated in MATLAB/Simulink to demonstrate the effect of the decreasing irradiance level on the maximum output power. In this chapter a PV Cell MATLAB/Simulink model is used to simulate a photovoltaic cell under different temperature conditions.

The results of the simulation demonstrate the effect the increasing ambient temperature has on the maximum power output of the cell.

3.2 Inputs

The inputs of the model are the same input used for MATLAB/Simulink in Chapter 2.

In this instance the irradiance level stays constant at Standard Test Conditions level of 1000 W/m², while the ambient temperature is varied. Photovoltaic cell is simulated in MATLAB/Simulink at the ambient temperatures of 5^0C, 25^0C and 45^0C.

The output current and the output voltage of a cell simulated under varied ambient temperatures were recorded. The results were used to produce I-V curves displayed in Figure 3.1.

Output power of the simulated cell at varied ambient temperatures was also recorded. The results were used to produce a power plot in Figure 3.2.

3.3 Results
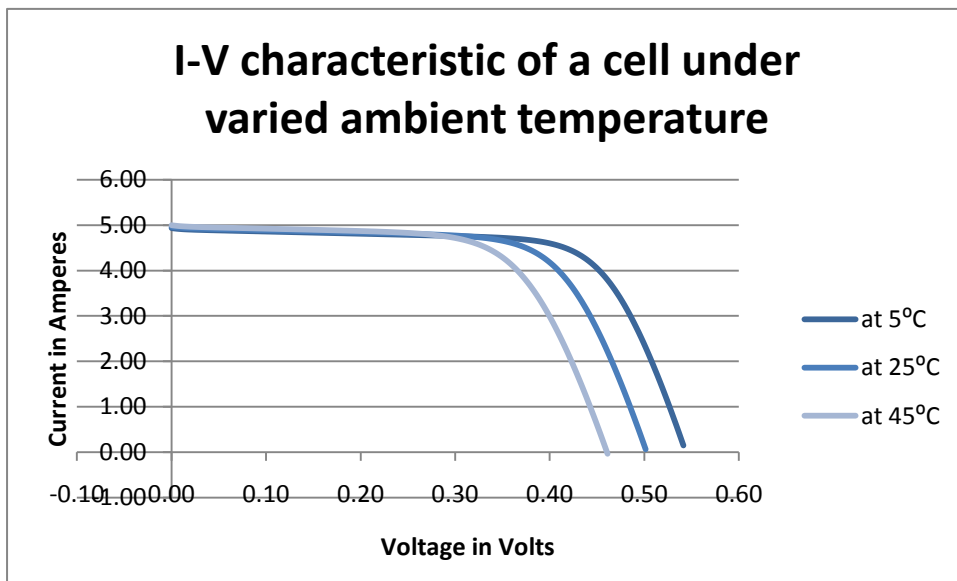
Figure 3.1 I-V characteristic of a cell under varied ambient temperature
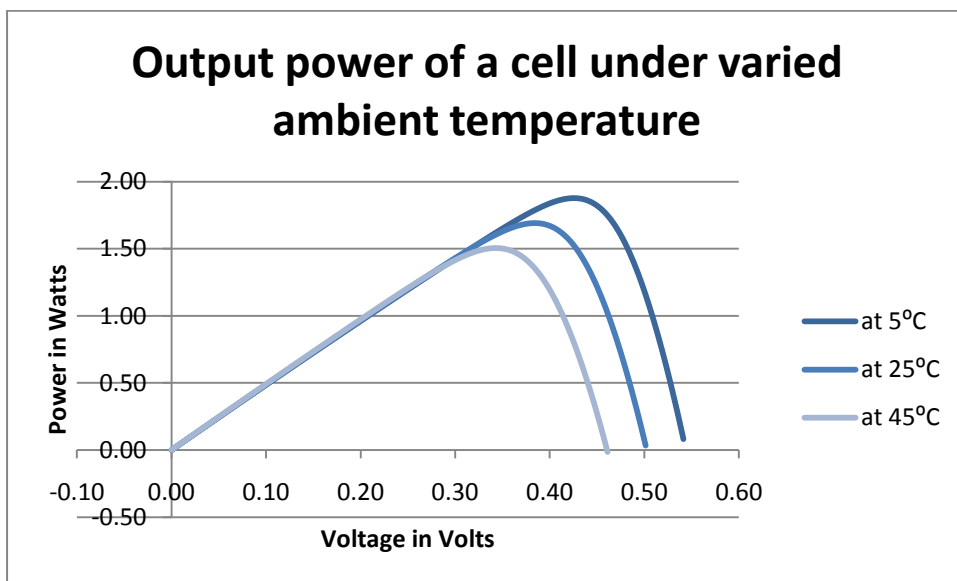
Figure 3.2 Output power of a cell under varied ambient temperature

Maximum power points of the cell under varied temperature			
Ambient temperature (⁰C)	Power at MPP (Watts)	Current at MPP (Amperes)	Voltage at MPP (Volts)
5	1.88	4.40	0.43
25	1.69	4.38	0.39
45	1.51	4.41	0.34

Figure 3.3 Maximum power point of a cell under varied temperature

3.4 Interpretation of the results

From Figure 3.2 and Figure 3.3, the maximum output power of a cell at the standard temperature of 25^0C was equal to 1.69 Watts. The cell would produce this maximum output power at the output voltage of 0.39 Volts and at the output current of 4.38 Amperes.

As the ambient temperature was increased from 25^0C to 45^0C, the maximum output power of the cell has decreased from 1.69 Watts down to 1.51 Watts. Increasing the ambient temperature around the array above the Standard Test Conditions decreases the maximum output of the cells and therefore decreases the maximum output of the modules. The cells would produce this maximum output power at the output voltage of 0.34 Volts and at the output current of 4.41 Amperes as showing in Figure 3.3.

As the ambient temperature was decreased from 25^0C to 5^0C, the maximum output power of the cell has increased from 1.69 Watts up to 1.88 Watts as showing in Figure 3.2 and Figure 3.3. Decreasing the ambient temperature around the array increases the maximum output of the cells and increases the maximum output of the modules. The cells would produce this maximum output power at the output voltage of 0.43 Volts and at the output current of 4.40 Amperes.

The ambient temperature influences the output power of the cell. As the ambient temperature is increased, the temperature of the cells increases and causes the output power of a photovoltaic cell to decrease. Therefore the temperature of the cells needs to be kept low for maximising the power output of the module.

3.5 Decreasing the cell's temperature

It is desirable for the module to be installed on a base that would allow wind to flow around the module, therefore cooling down the module. As the temperature of the photovoltaic cell is decreased by the wind, the efficiency and the output of the module will be increased.

3.6 Conclusion

MATLAB/Simulink software was useful to understand the effects of global irradiation and the ambient temperature on the power generated by the cell. The models simulated might be useful for future students studying Renewable Energy, as the program makes it easy to vary the inputs and save the results.

More than one cell is required for displaying the effect of partial shading on the output of a module. As the previous simulations in Simulink were based on equations, adding more photovoltaic cells and bypass diodes to display the effect of partial shading on the module will make equations more complicated. Therefore the rest of the simulations were done using the circuit simulator ICAP/4.

Chapter 4 Partial shading

4.1 ICAP simulations

ICAP/4 (*ICAP/4*) software was used to simulate partial shading of the module. The method and results of those simulations are being described in this chapter.

4.1.1 PV cell in ICAP/4

A single solar cell was simulated in ICAP/4. The model consisted of a current source, a diode, a series resistance and a shunt resistance, as shown in Figure 4.1.
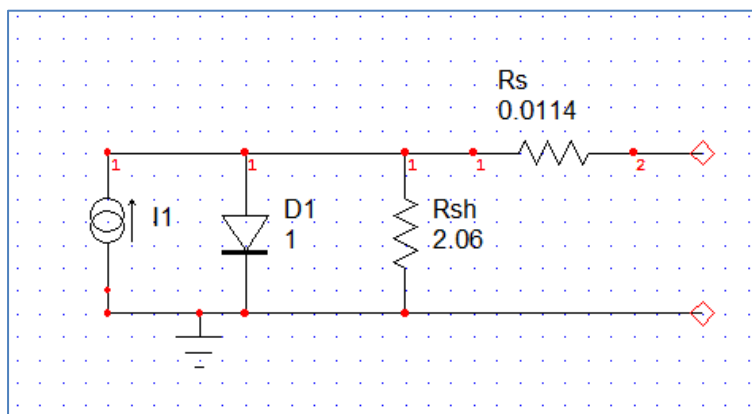
Figure 4.1 Photovoltaic cell simulated in ICAP/4

The input for the simulation in ICAP/4 was the data from Thompson's thesis, *op. cit.* The short circuit current of the cell was 4.92 Amperes. The shunt resistance was 2.06 Ohms. The diode saturation current was 1.59 x 10^{-9} Amperes and the series resistance was 0.114 Ohms.

As it was mentioned in Chapter 1, shading of a cell in the module can cause the cell to operate in its reverse bias state, thereby consuming power instead of generating the power. Shaded cell can heat up and be damaged under those conditions.

Bypass diodes are used to decrease the effect of partial shading on the output of the modules and to decrease the chances of the shaded cells being over-heated (*Diodes in PV Systems).*

A model of a photovoltaic single cell with a bypass diode is shown in Figure 4.2.

A bypass diode is placed across the cell, in the opposite direction to the cell's diode as shown in Figure 4.2. When a cell is being shaded, the current coming from the unshaded cells has a path through the bypass diode. Bypass diodes help to keep the output of the module up when some cells are in the shade.

4.1.2 PV module in ICAP/4

A configuration of a module consisting of 36 cells in series is shown in Figure 4.3. This module is simulated in ICAP/4 to demonstrate the effect of partial shading on the power output of the module. The module did not have bypass diodes.

The module was simulated without shading. The results were saved and plotted in Excel. Then the module was simulated with one cell being shaded, two cells being shaded and three cells being shaded.

The results of current and voltage of the cells are plotted as I-V characteristic curves of the module in Figure 4.5. The output power of the module with partial shading is displayed in Figure 4.6.
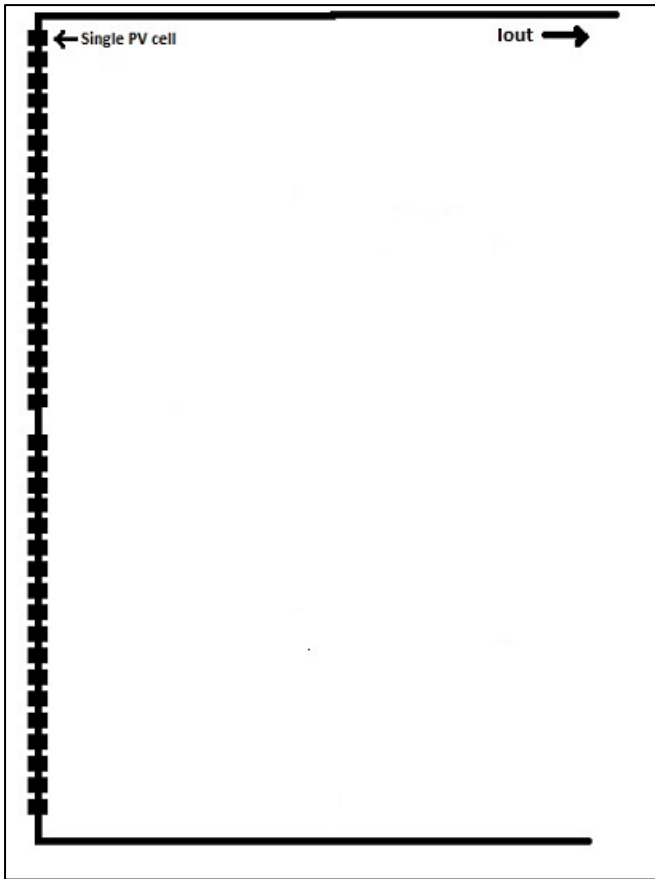
Figure 4.3 PV module without bypass diodes

4.1.3 PV module with by-pass diodes

Ideally, each cell of the module would have a bypass diode. If one cell is shaded then just that cell would be by-passed, therefore the power output of the module would not be affected that much.

 Partial shading of a module was simulated in ICAP/4. Each cell had a bypass diode. The module was simulated under no shade, with one cell, 2 cells and 3 cells shaded.

Results of the simulations were saved and plotted in Excel. The I-V characteristic of the module with a bypass diode across each cell under those conditions is shown in Figure 4.7. The output power of the module with 36 bypass diodes with partial shading is displayed in Figure 4.8.

Having a bypass diode across each cell is expensive. It complicates the circuit and takes time to do. Therefore usually a photovoltaic module has only 2 or 3 bypass diodes.

A configuration of a module with two by-pass diodes is shown in Figure 4.4. Each bypass diode is placed across 18 cells in series.
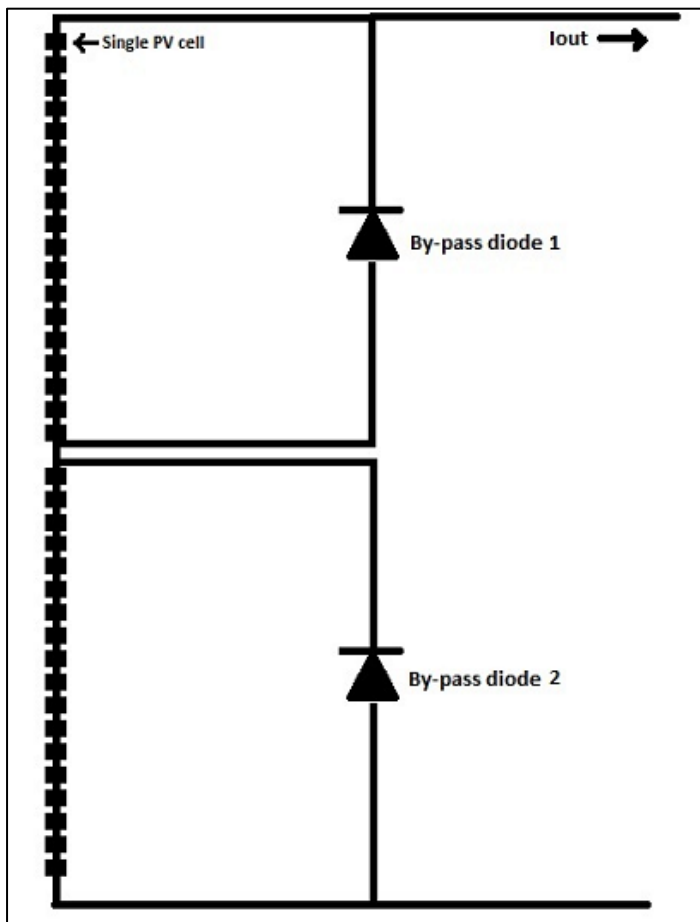
Figure 4.4 PV module with two bypass diodes

A PV module with 2 bypass diodes was simulated in ICAP/4. It was simulated without shading and then with one, two and three fully shaded cells. The results were saved and plotted in Excel. I-V curve of the module with two bypass diodes under those conditions is shown in Figure 4.9. Plot of output power of the module under those conditions is shown in Figure 4.10.

After that a module with configuration displayed in Figure 4.4 was simulated in ICAP/4 with one cell being half-shaded. I-V curve of the module with one half-shaded cell is shown in Figure 4.11. The plot of the output power of the module with one cell half-shaded is shown in Figure 4.12.

4.1.4 Comparison between the models

The I-V characteristic of a single photovoltaic cell simulated in ICAP/4 is shown in Figure 4.16. The same plot shows an I-V characteristic of a cell simulated this thesis' and Wichert's MATLAB/Simulink models, *op. cit*. Figure 4.16 also shows the results recorded by Thompson, *op. cit*.

The power plot of a single photovoltaic cell simulated in ICAP/4 is shown in Figure 4.17. The same plot shows a power plot of a cell simulated using the PV Cell model and Wichert's MATLAB/Simulink model, *op. cit.* Figure 4.17 also shows the results recorded during the tests by Thompson, *op. cit.*

Short-circuit current, open-circuit voltage and maximum output power of the cell simulated by ICAP/4, MATLAB/Simulink and recorded by Thomson, *op. cit.,* are shown in Figure 4.18.

4.2 Results
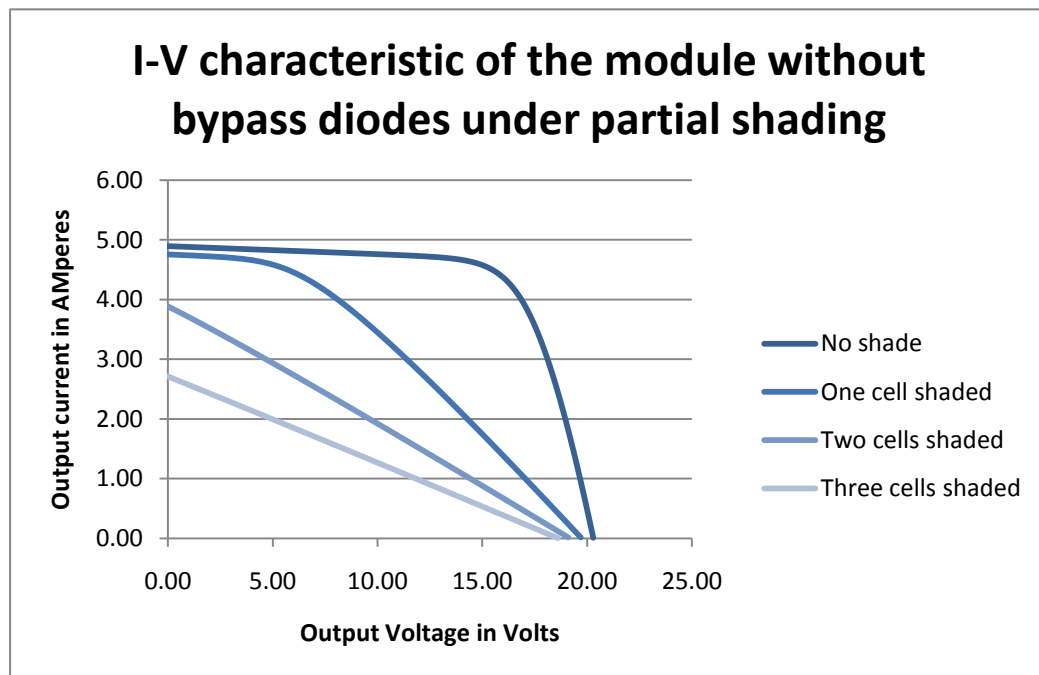
Figure 4.5 I-V characteristic of the module without bypass diodes under partial shading
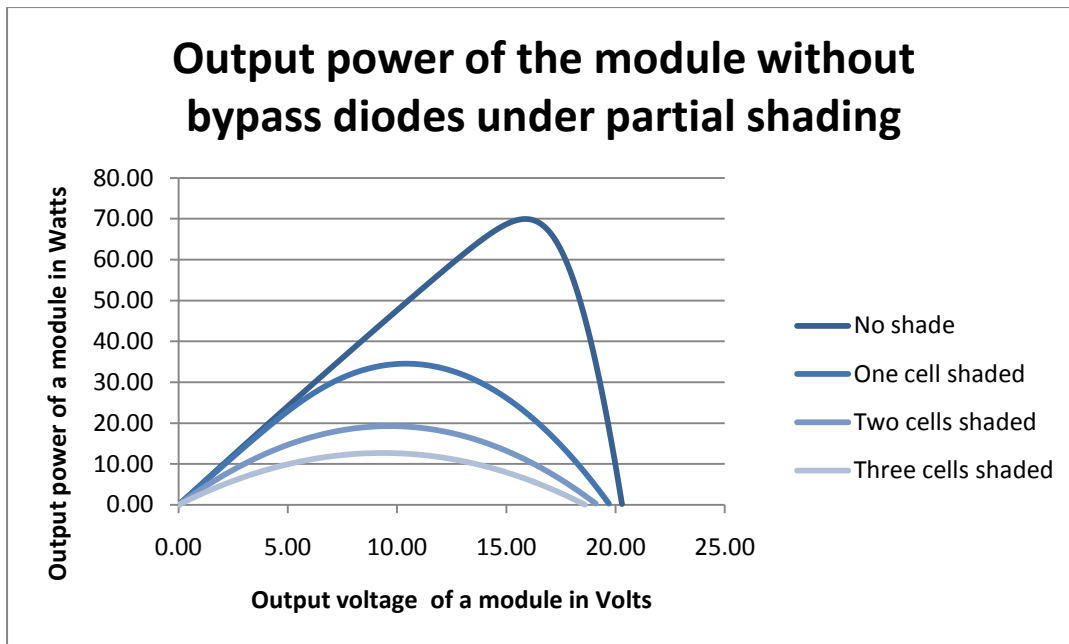
Figure 4.6 Output power of the module without bypass diodes under partial shading

Maximum output power of the module without bypass diodes under partial shading			
	Power at MPP (Watts)	Current at MPP (Amperes)	Voltage at MPP (Volts)
No shade	69.93	4.40	15.90
One cell shaded	34.58	3.33	10.40
Two cells shaded	19.25	1.98	9.70
Three cells shaded	12.72	1.37	9.30

Figure 4.7 Maximum output power of the module without bypass diodes under partial shading

I-V characteristic of a module with 36 bypass diodes under partial shading

Output current in Amps

- No shade
- One cell shaded
- Two cells shaded
- Three cells shaded

Output voltage of a module in Volts
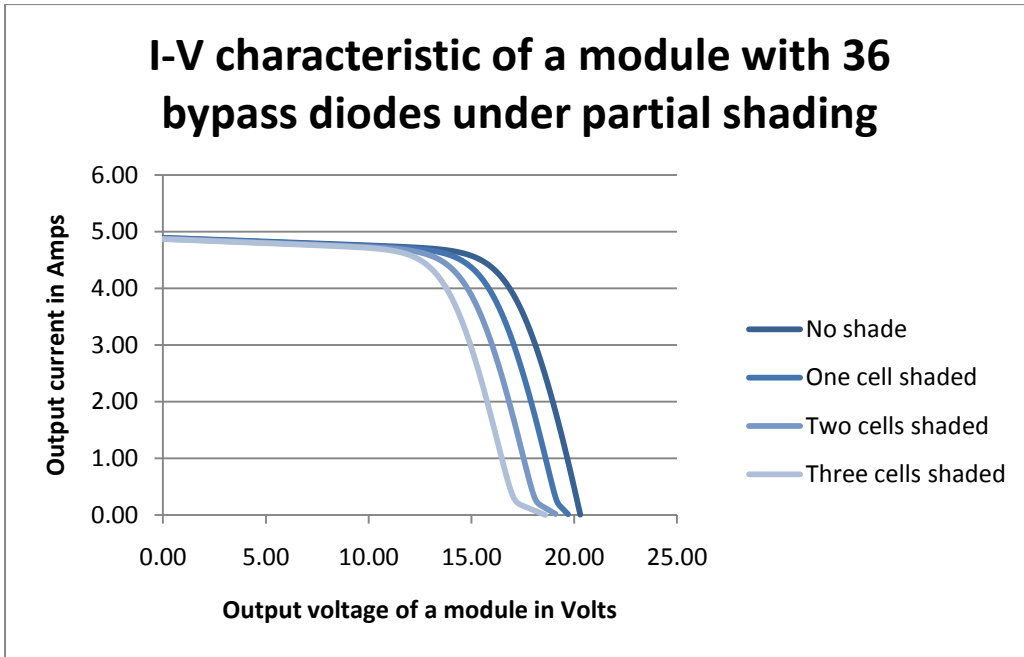
Figure 4.8 I-V characteristic of the module with 36 bypass diodes under partial shading

Output power of the module with 36 bypass diodes under partial shading

- No shade
- One cell shaded
- Two cells shaded
- Three cells shaded
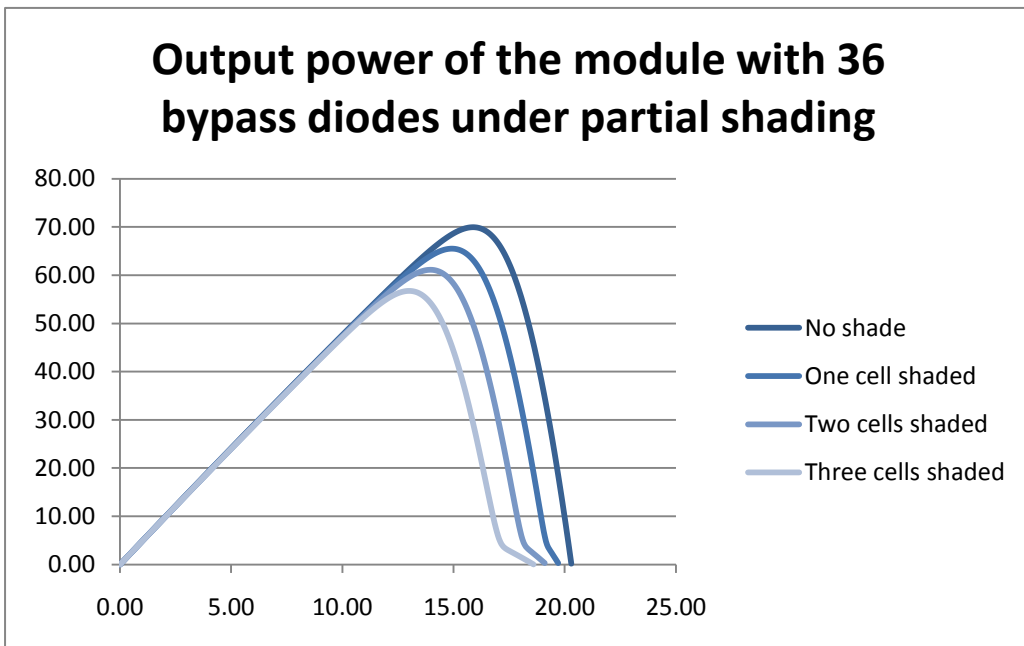
Figure 4.9 Output power of the module with 36 bypass diodes under partial shading

Maximum output power of a module with 36 bypass diodes under partial shading			
	Power at MPP (Watts)	Current at MPP (Amperes)	Voltage at MPP (Volts)
No shade	69.93	4.40	15.90
One cell shaded	65.52	4.40	14.90
Two cells shaded	61.12	4.37	14.00
Three cells shaded	56.73	4.36	13.00

Figure 4.10 Maximum output power of the module with 36 bypass diodes under partial shading
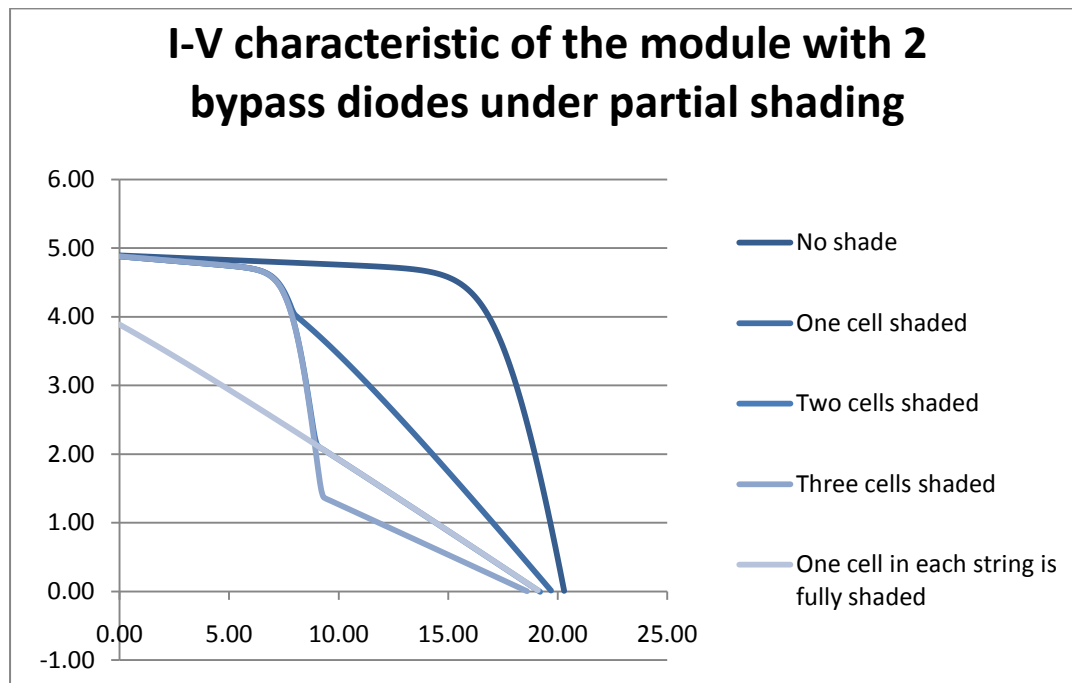
Figure 4.11 I-V characteristic of the module with 2 bypass diodes under partial shading
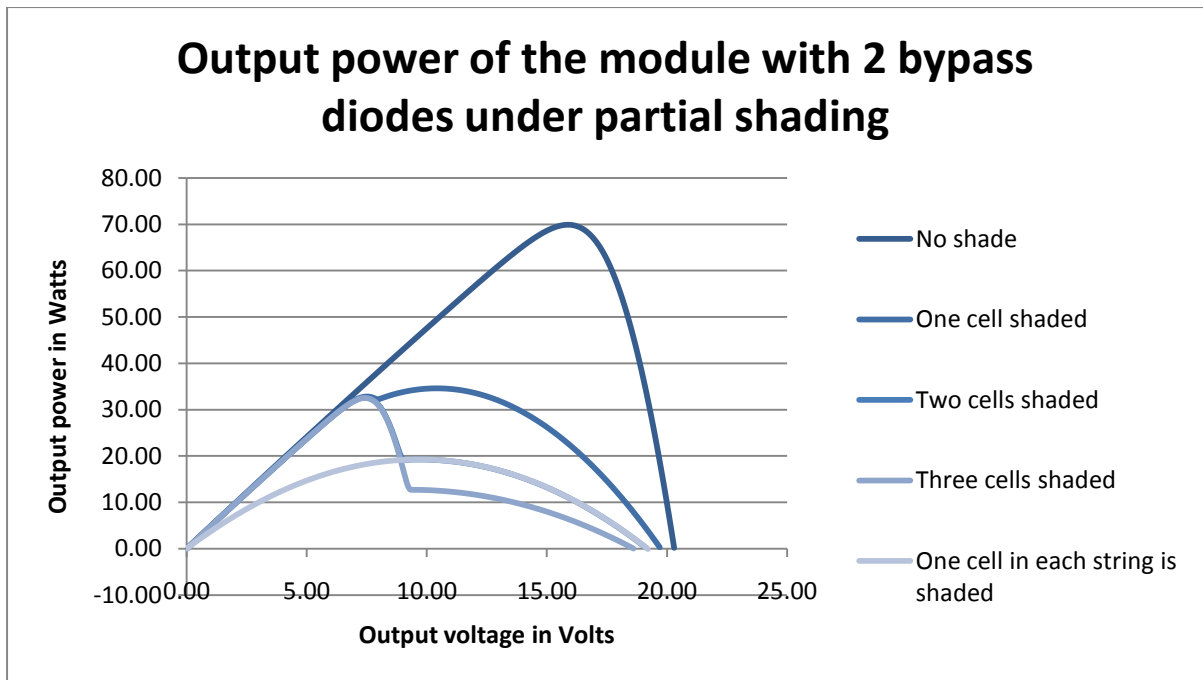
Figure 4.12 Output power of the module with 2 bypass diodes under partial shading

Maximum output power of the module with 2 bypass diodes under partial shading			
	Power at MPP (Watts)	Current at MPP (Amperes)	Voltage at MPP (Volts)
No shade	69.93	4.40	15.90
One cell shaded	34.58	3.33	10.40
Two cells shaded	32.59	4.40	7.40
Three cells shaded	32.56	4.40	7.40
One cell in each string is fully shaded	19.24	1.98	9.70

Figure 4.13 maximum output power of the module with 2 bypass diodes under partial shading
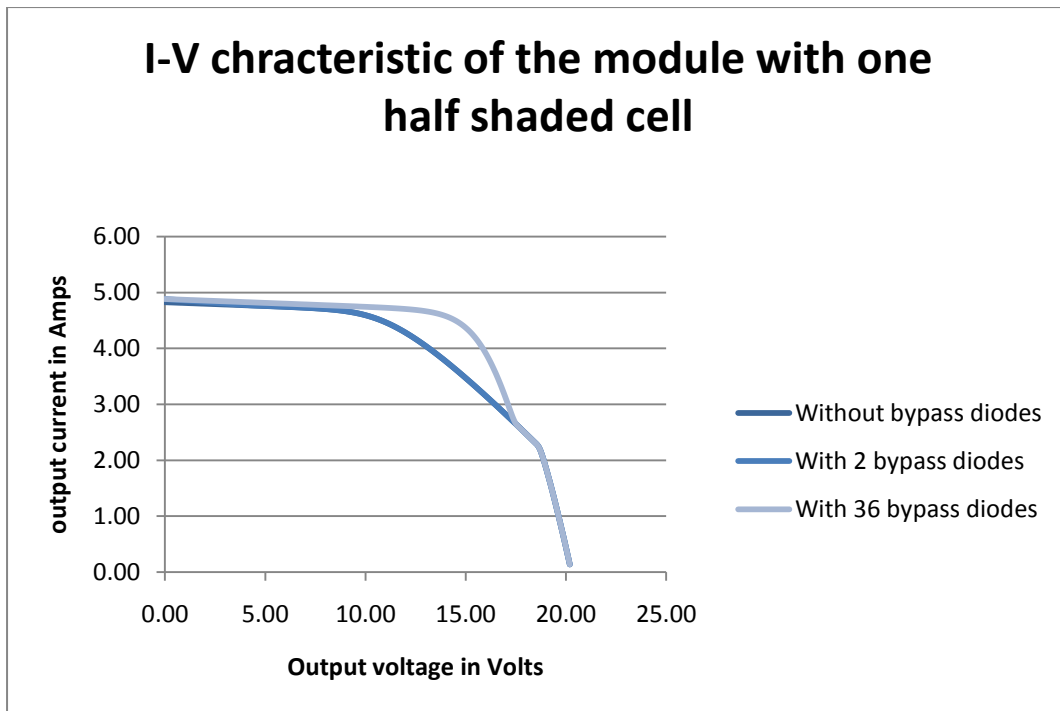
Figure 4.14 I-V characteristic of a module with one half-shaded cell
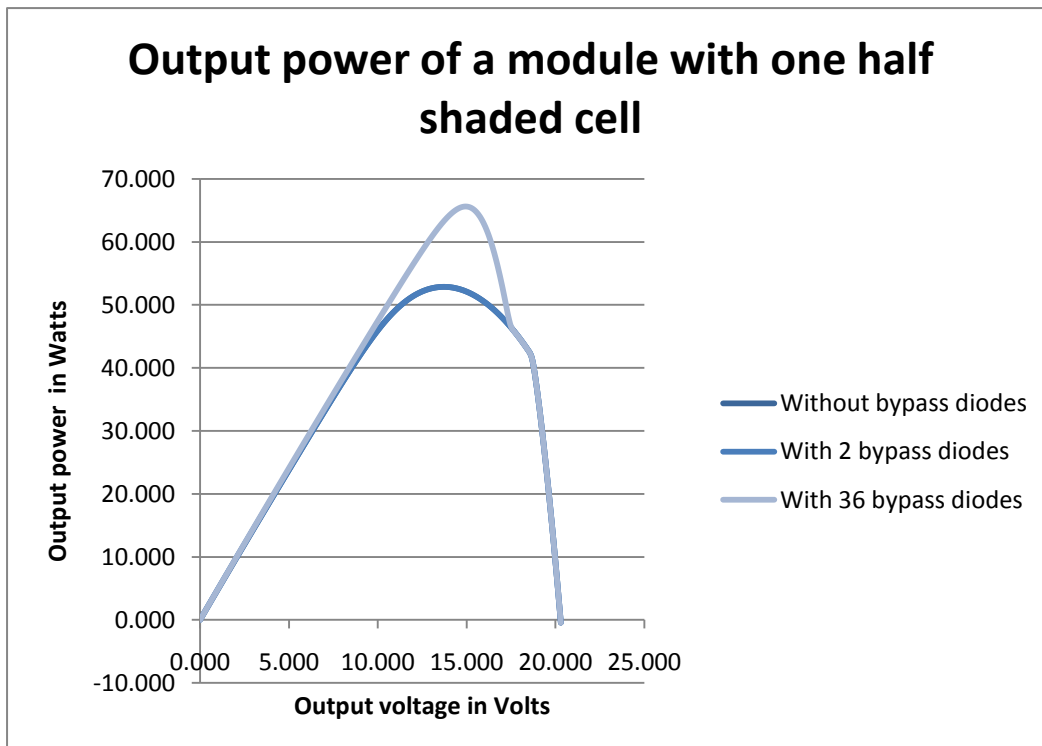
Figure 4.15 Output power of a module with one half-shaded cell

I-V curve of the PV cell produced by different programs

Figure showing output current in Amperes (y-axis, -1.00 to 6.00) versus output voltage in Volts (x-axis, -0.20 to 0.80). Legend:
- Wichert's MATLAB/Labview Simulation
- ICAP/4
- Thompson's recorded values
- My MATLAB/Labview simulation
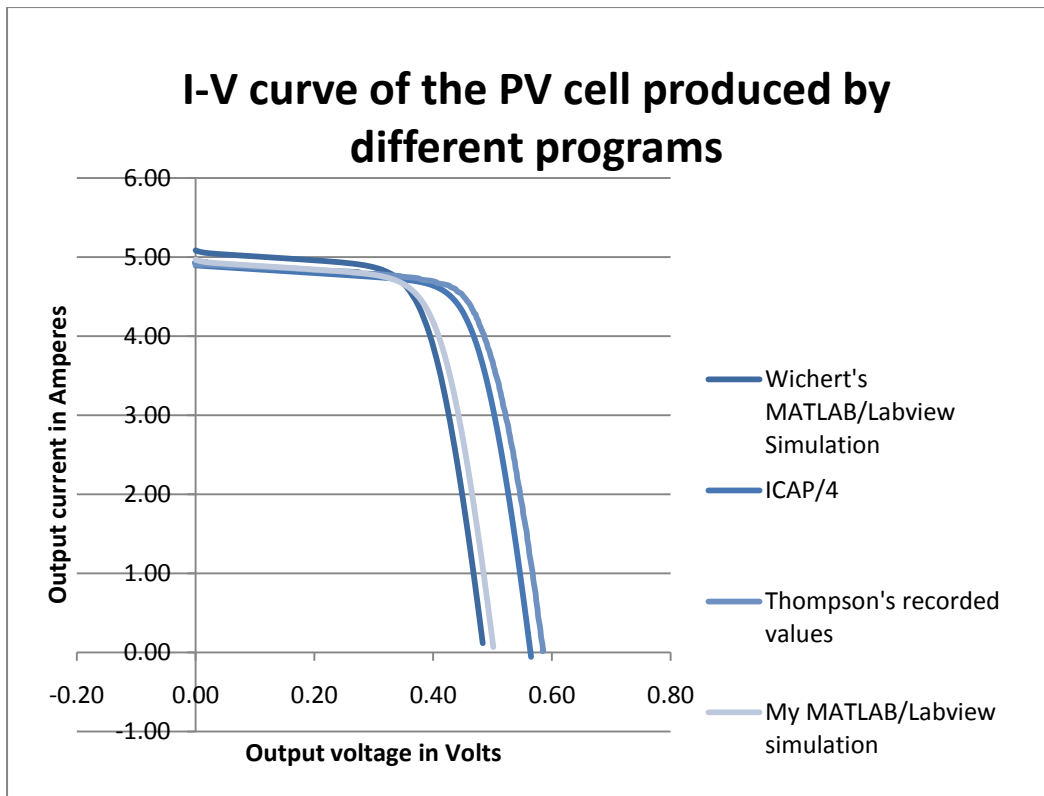
Figure 4.16 I-V curve of the PV cell simulated by different programs

Output power of the PV cell produced by different programs

Figure showing output power of a cell (y-axis, -0.50 to 2.50) versus output voltage in Volts (x-axis, -0.20 to 0.80). Legend:
- My MATLAB/Labview program
- Wichert's MATLAB/Labview program
- ICAP/4
- Thompson's recorded values
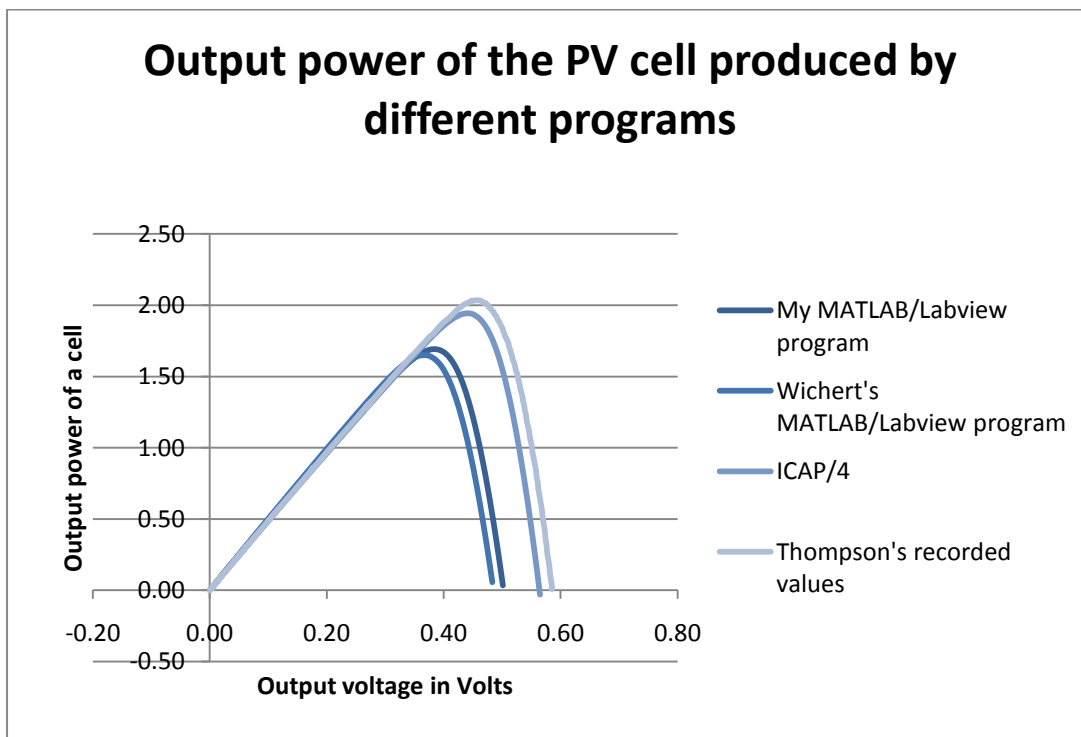
Figure 4.17 Output power of the cell simulated by different programs

Maximum power output of the cell produced by different programs			
	Short-circuit current (Amperes)	Open-circuit voltage (Voltage)	Maximum Output Power (Watts)
This thesis' Labview simulation	4.97	0.50	1.69
Wichert's Labview simulation	5.09	0.48	1.65
ICAP/4	4.89	0.57	1.94
Thompson's recorded results	4.93	0.59	2.03

Figure 4.18 Maximum power output of the cell simulated by different programs

4.3 Interpretation of the results

4.3.1 Module without bypass diodes

Figure 4.5 and Figure 4.6 show the output current and the output power of the module simulated in ICAP/4 under shaded conditions. The module consists of 36 cells connected in series without bypass diodes.

The maximum power produced by the simulated module without shading is 69.93 Watts as shown in Figure 4.7. The module would be generating this maximum power at the voltage of 15.90 Volts and at the current of 4.40 Amperes.

The output power of a module drops when one cell is shaded. The maximum output power of a module without a bypass diode drops from 69.93 Watts down to 34.58 Watts when one cell is fully shaded. In the case of two cells being fully shaded the maximum output of the module is 19.25 Watts. The maximum power output of the module without bypass diodes with three cells fully shaded is 12.72 Watts.

From the simulation, one fully shaded cell decreases the power output of the 36 cell module without bypass diodes by approximately a half. From the results, the more fully shaded cells there are in the module without bypass diodes, the smaller the maximum output power of the module.

As it was mentioned before, bypass diodes can be used in the modules to decrease the effect of partial shading on the power output of the module and to decrease the chances of overheating of the shaded cell.

4.3.2 Module with a bypass diode connected in parallel to each cell

Figure 4.8 and Figure 4.9 show the I-V characteristic and the power plot of the module simulated in ICAP/4 with a bypass diode connected in parallel to each cell. The module consists of 36 cells connected in series and has 36 bypass diodes. This configuration is too expensive and not practical. However, simulation of this case in ICAP/4 shows that the maximum output power of the cell is only slightly affected if one cell is shaded.

The maximum power produced by the module without shading is 69.93 Watts as shown in Figure 4.10. The simulated module generates this maximum power at the voltage of 15.90 Volts and at the current of 4.40 Amperes.

The maximum output power of this module with one cell fully shaded decreases from 69.93 Watts to 65.52. The simulated photovoltaic module generates this power at the voltage of 14.90 Volts and at the current of 4.40 Amperes.

The maximum output power of this module with two cells fully shaded is 61.12 Watts. The simulated photovoltaic module generates this power at the voltage of 14 Volts and at the current of 4.37 Amperes.

The maximum output power of this module with three cells fully shaded is 56.73 Watts. The simulated photovoltaic module generates this power at the voltage of 13 Volts and at the current of 4.36 Amperes.

This simulation shows that placing a lot of bypass diodes in the module decreases the effect of shading on the output power of the module. In practise one bypass diodes is connected across a group of photovoltaic cells.

4.3.3 Module with 2 bypass diodes

Figure 4.11 and Figure 4.12 show the I-V characteristic and the output power plot of the module simulated in ICAP/4 with 2 bypass diodes in shading conditions.

The maximum output power of the module with two bypass diodes without shading is 69.93 Watts as shown in Figure 4.13.

The maximum power of the module with two bypass diodes and one fully shaded cell is 34.58 Watts as shown in Figure 4.13. The maximum power is generated by this module at the voltage of 10.40 Volts and at the current of 3.33 Amperes.

The maximum power of the module with two fully shaded cells along the same bypass diode is 32.59 Watts as shown in Figure 4.13. The maximum power of the module with three cells fully shaded along the same bypass diode is 32.56 Watts as shown in Figure 4.13.

When one cell in the module is fully shaded the current will go through the bypass diode. The module has 2 bypass diodes. Each diode is connected across a group of 18 cells in series. When one cell is shaded, then all 18 cells in the same group are bypassed and the maximum power of the module drops from 69.93 Watts down to 34.58 Watts. The maximum output power drops by approximately a half. However, it is still a much better result than the maximum power output of the module without by-pass diodes with one cell fully shaded.

When two cells along the same bypass diode are shaded the maximum output power is similar to the maximum output power of a module with one cell shaded. However, if one cell parallel to each by-pass diode was shaded then the maximum power output drops from 69.93 Watts down to 19.24 Watts as showing in Figure 4.13. It is unlucky for one in each string to be fully shaded.

4.3.4 Module with a half-shaded cell

Figure 4.14 and Figure 4.15 show the results of a simulation of the module in ICAP/4 without bypass diodes, with 2 and 36 bypass diodes where one cell is half-shaded.

The I-V characteristic of the module with one cell half-shaded in parallel to one of 2 bypass diodes has two power points as shown in Figure 4.15. The Maximum Power Point Trackers are used to adjust the voltage of the module so it operates at the maximum power point. A Maximum Power Point Tracker in this case would make the model work at one of the maximum power points. However, in this case power point trackers would not know of the existence of the second maximum power point. Therefore the tracker would cause the module to work at one of the maximum power

points without checking which maximum power point of the two would generate more power. Maximum Power Point Trackers are explained in more detail in Chapter 5.

4.3.5 Comparison between the models

Figure 4.16 and Figure 4.17 show the I-V curves and the power curves of a photovoltaic cell simulated in ICAP/4, MATLAB/Simulink and the results recorded by Thompson, *op. cit.,* during the experiment.

From Figure 4.16 and Figure 4.17, the results produced by simulation of a photovoltaic cell in ICAP/4 are close to results recorded during the experiment by Thompson, *op. cit.* The results are close because the series resistance, shunt resistance and the diode saturation current were calculated by Thompson, *op. cit.*, from experimental results to be used in ICAP/4. However, the open-circuit voltage and the short-circuit current recorded by Thompson*, op. cit.*, during the experiment are slightly different from the open-circuit voltage and the short circuit current of a photovoltaic cell recorded during ICAP/4 simulation, as shown in Figure 4.18. Thompson, *op. cit.*, also had a difficulty matching the measured results with the results produced by simulation in ICAP/4. Further research and calculations will need to be done in this area.

From Figure 4.16 and Figure 4.17, the results produced by simulation of a photovoltaic cell using my MATLAB/Simulink model are close to the results produced using Wichert's MATLAB/Simulink model, *op. cit.* This is because all the equations used in this paper's MATLAB/Simulink model are based on equations described by Wichert*, op. cit*. The inputs of both programs are the same. However, the open-circuit voltage and the short-circuit current of a cell recorded using my MATLAB/Simulink are slightly different to the open-circuit voltage and the short-circuit current produced by Wichert's MATLAB/Simulink model, *op. cit*. This is probably due to different ways the equations are connected. I've connected the equations using "Go To" and "Go From" functions of MATLAB/Simulink, while Wichert, *op. cit.*, connected the equations using "Masks".

There is a big difference in the open-circuit voltage of the cell simulated using MATLAB/Simulink models and the open-circuit voltage of the cell simulated using ICAP/4 model. This is probably due to the fact that the ICAP/4 model required few inputs, while both MATLAB/Simulink programs required more inputs to demonstrate

the effect of ambient temperature on the output power of the cell. Each of those inputs would have an effect on the final output of the simulation.

4.4 Decreasing the effect of partial shading on the output power of the module

Shading decreases the power output of the module, as it was demonstrated by the simulations in ICAP/4. It is preferable that there is no shade falling on the module. Trees and buildings could shade a module during certain times of the day. Shading from the surrounding objects over the course of the day should be investigated before installation of the module.

Bypass diodes are used to decrease the negative effect of shading on the output power of the module and to protect cells from overheating. Bypass diodes are connected across a group of cells and provide an alternative route for current to flow in the case of shading. The modules that have bypass diodes can still provide sufficient amount of power under shaded conditions, while the output power of the modules without bypass diodes drops dramatically even if just one cell is shaded.

Shading could also be caused by dust, dirt and snow covering the cells. Therefore general cleaning of the modules from time to time decreases the impact of shading.

During the times when there is no sunlight falling on the modules, an array can act as a load and draw the power from the battery. A blocking diode is placed between modules and battery to stop the module from discharging the battery during the night time.

5 Maximum Power Point Tracker

5.1 Introduction

Maximum Power Point Trackers adjust the load voltage of the photovoltaic module so it operates at its maximum power point. Maximum Power Point Trackers usually consist of a DC/DC converter, a Pulse Width Modulation Unit and a controller (Castaner, Luis, and Silvestre 2001, 147).

The I-V curve of the module could change due to changes in the operating conditions. Changes in the ambient temperature and the global irradiance influence the I-V curve of the module. Shading also affects the I-V curve of the module. A Maximum Power Point Tracker adjusts the operating point of the module to a new maximum power point when there are changes in the I-V curve of the module.

DC/DC converters are used as a part of the Maximum Power Point Trackers. Buck and Boost DC/DC converters are described below.

5.2 Buck converter

A circuit of a Buck converter is displayed in Figure 5.1. It consists of a switch, a diode, an inductor and a capacitor. The configuration of the elements inside the Buck converter ensures that the output voltage of the inverter is smaller than the input voltage (Castaner, Luis and Santiago Silvestre 2001).

The photovoltaic module is connected to the input of the buck converter. The input voltage of the converter is equal to the load voltage of the module. The input voltage of the converter is varied by changing the duty cycle of the switching operation, until the module operates at its maximum power point.
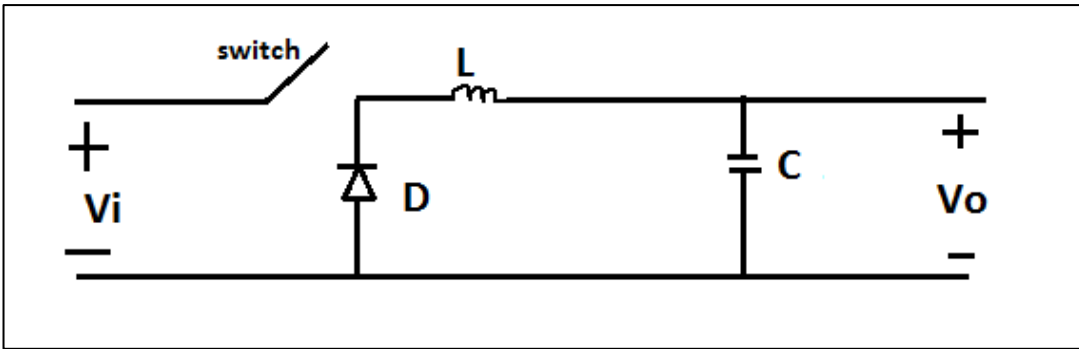
Figure 5.1 Buck converter

5.3 Boost converter

A circuit of a Boost converter is displayed in Figure 5.2. Boost DC/DC converter consists of the same elements as the Buck converter. Those elements are an inductor, a diode, a capacitor and a switch, but the elements are connected in a different way compared to Buck converter (Castaner, Luis and Santiago Silvestre 2001). The configuration of the elements in the Boost converter ensures that the output voltage is higher than the input voltage.

Figure 5.2 Boost converter

The photovoltaic module is connected to the input of the DC/DC converter. The input voltage of the inverter is equal to the load voltage of the photovoltaic module. The input voltage of the Boost DC/DC converter is varied, until the photovoltaic module operates at its maximum power point.

5.4 MPPT circuit

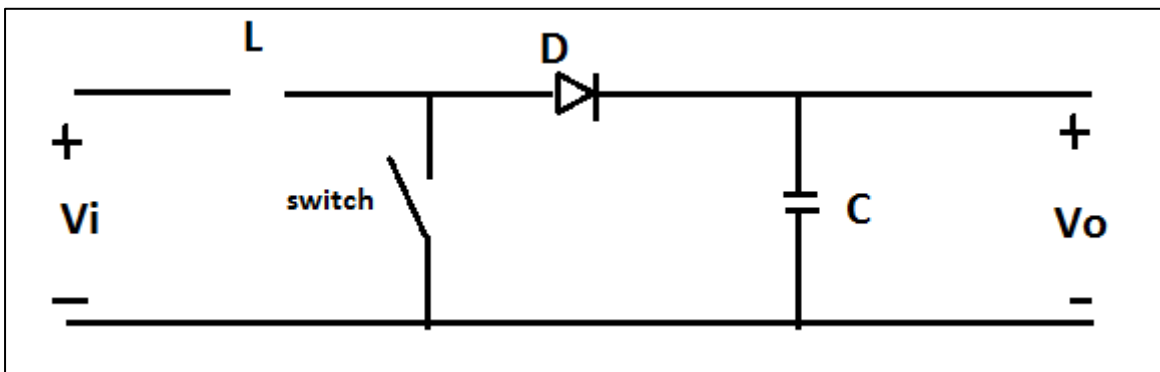The operation of the switch in the DC/DC converter is controlled by Pulse Width Modulation.

Pulse Width Modulation is governed by a controller.

The Controller analyses the output current and the load voltage of the module. Based on the output data of the module the controller sends a signal to the Pulse Width Modulator. The Pulse Width Modulator adjusts the operation of the switch in the DC/DC controller, thereby adjusting the load voltage of the module (Gules 2008).

The output current and the load voltage of the module are measured again by the controller. Load voltage of the module is adjusted until the module is operating at its maximum power point.

There are different ways in which the MPPT is connected to the circuit. Series connection would have a dc-dc controller connected in series between source and load. Series connection of the converter is used as a battery charger and a MPPT.

A dc-dc controller can also be connected in parallel to a photovoltaic module (Gules 2008). The advantage of this configuration is that only a fraction of the available power that goes through the converter, therefore less power is lost through the converter. Parallel connection of the MPPT has a higher efficiency than the series connection (Gules 2008).

Maximum Power Point Trackers can also be used for decreasing the output power of the module. The power output of the module will need to be limited when the system's load is low or the battery is fully charged.

The Maximum power point of the module could shift due to changes in the operating conditions, as was seen in the results of this report. A Controller would notice those changes and would adjust the load voltage of the module so that it operates at the maximum power point.

5.5 Control methods

There are different control methods used in Maximum Power Point Trackers. The control methods are used to find the maximum power point of the module. Then with help of Pulse Width Modulation and DC/DC converter the load voltage of the module is adjusted, so the module operates at the maximum power point.

Some of the popular control methods used for finding the maximum power point of the module are Perturb and Observe and Incremental Conductance (Chen and Lin 2011, 1621).

The Perturb and Observe method is often called a Hill Climbing method. This method uses the measured output current and operating voltage to calculate output power of the module. The direction and the step size of duty cycle perturbation are adjusted until the maximum power point is reached (Nordin and Omar 2011, 114). The algorithm for the Perturb and Observe method is useful when the changes in the system do not happen quickly (Chen and Lin 2011, 1621).

The Incremental Conductance method uses the measured changes in the output voltage and the output current of the photovoltaic array to track maximum power point. Then the operating voltage of the module is adjusted according to the maximum power point voltage (Safari and Mekhilef 2011, 1154). The Incremental Conductance method is more effective than the Hill Climbing method (Chen and Lin 2011, 1621).

Changes in the operation conditions cause changes in the I-V characteristic of the module. Shading also decreases the maximum power point of the I-V characteristic. The Controller measures the output data from the module. From the measured data, the controller notices changes in the I-V curve and adjusts the operating point of the module then it operates at the new maximum power point. Maximum Power Point Trackers are also used for changing the operating point of the module so it provides less power when the load is small and the battery is fully charged.

Chapter 6 Future work

Future researcher could work on developing a model of a photovoltaic cell using Power Factory software. Power Factory provides an option of creating new models. The number of inputs and outputs of the model can vary and the equations can be used to relate those inputs to the outputs. Equations described in this thesis could be used for simulation of the photovoltaic cell in Power Factory.

There is also an option of creating a photovoltaic model in MATLAB and then uploading a MATLAB file into Power Factory. However, that only applies to the MATLAB programming language and does not apply to MATLAB/Simulink models. A model of a photovoltaic cell in Power Factory is desirable as the recent version of the program does not have the photovoltaic cell model.

Further research needs to be made about the series and shunt resistances values that could bring the results of a simulation closer to the experimental results.

Maximum Power Point Trackers were explained in this thesis to some degree. Maximum Power Point Tracker operation in different operating conditions could be simulated and investigated. There are many examples of it being simulated in MATLAB/Simulink and PSPICE, offering different techniques of control.

Conclusion

Effects of operating conditions on the output of the photovoltaic cell and a module were investigated in this thesis.

A photovoltaic cell was simulated in MATLAB/Simulink using the global irradiance conditions in the range of 250 W/m² to 1000 W/m². From the simulations, as the global irradiance was decreased the maximum power output of the cell of the cell decreased. Therefore, for a cell to provide the maximum output power the amount of the global irradiance should be maximised.

A photovoltaic cell was simulated in MATLAB/Simulink to investigate the effects of varying the ambient temperature in the range of 5⁰C to 45 ⁰C. From the results, as the ambient temperature was increased, the output power of the cell decreased. Therefore low ambient temperatures and cell temperatures are optimal.

Partial shading of a photovoltaic module was simulated in ICAP/4. The simulations showed that shading decreased the power output of the module. Bypass diodes are used to decrease the effect of partial shading on the power output of a module. A module was simulated with bypass diodes under different shading conditions. From the results, bypass diodes decreased the negative effect of partial shading on the power output of the module.

Maximum Power Point Trackers were described as devices that ensure the module is operating at its maximum power point, even if the I-V curve of the module is changing due to changes in the operating conditions.

Future researcher could use the models from this thesis for simulating and understanding the effects of the operation conditions on the power output of the module. Researcher doing similar work in future can go into simulating a photovoltaic cell in Power Factory using the equations described in this thesis, as the current version of Power Factory does not have a photovoltaic cell model. Simulation of Maximum Power Point Trackers could also be done using one of the programs mentioned above.

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Appendix A: Equations

As it was mentioned in Chapter 2, the equations used in the PV Cell MATLAB/Simulink model are based on the equations described by Wichert, *op. cit.*

1. Output current of the cell was calculated from equation (1), which is repeated here: *I=Iph-Id-Ish*   equation (1)

2. Current through the shunt resistance:

    Ish = (V + I x Rs) / Rsh   equation (2)

3. Photocurrent was calculated using equation:

    $Iph = \ Ir\ x\ \frac{Isc}{Iro} + It\ x\ (Tc - Tref\ )$ equation (3)

Equation (3) demonstrates that the photocurrent *Iph* is proportional to the irradiance *Ir* and the temperature of a cell *Tc*. The increase in the irradiance *Ir* will increase the photocurrent *Iph.* The increase in the temperature of a cell *Tc* will increase the photocurrent *Iph* slightly.

4. Temperature of a photovoltaic cell was calculated using equation:

    $Tc = Ta + Ir\ \ x\ (\frac{NOCT-20}{800})$ equation (4)

Equation (4) demonstrates that the temperature of a photovoltaic cell *Tc* is proportional to the irradiance *Ir* and the ambient temperature *Ta.*

5. Current going through the diode was calculated using equation:

    $Id = Is\ x\ (\ e^{(\frac{q}{Tc\,x\,n\,x\,K}(I\ x\ Rs+V))}\ - 1)$ equation (5)

6. The inverse saturation current of the pn junction will increase with increasing temperature *(Diode equation)*. It is calculated using the equation:

    $Is = Io\ x\ (\frac{Tc}{Tr})^3\ x\ \ e^{((\frac{q\,x\,Eg}{n\,x\,K})\,x\,(\frac{1}{Tr}-\frac{1}{Tc}))}$ (equation 6)

Appendix B: The CD Contents

1. Electronic copy of thesis
2. MATLAB/Simulink model of a cell
3. ICAP/4 models
4. Results