

**STUDY OF INTERCONNECTION OF SOLAR CELLS WITHIN A SOLAR
PANEL TO TACKLE THE SHADING PROBLEMS**

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**A project report submitted in partial fulfilment of the
requirements for the award of Bachelor of Engineering
(Hons.) Electrical and Electronic Engineering**

**Faculty of Engineering and Science
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April 2016

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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Specially dedicated to
my beloved mother and father,
and supervisor Dr. Lim Boon Han.

STUDY OF INTERCONNECTION OF SOLAR CELLS WITHIN A SOLAR PANEL TO TACKLE THE SHADING PROBLEMS

ABSTRACT

In recent years, the depletion of fossil fuel and the serious problem of environmental pollution has pushed the development and uses of renewable energy. One of the most widely use renewable energy is solar energy. Photovoltaic (PV) panel is used to harness the solar energy and directly convert it into electricity. As solar is gaining popularity in the recent years, many of the research had also studied to increase the performance of PV panel. One of the biggest drawbacks for PV panel is the power losses when subject to shading. The traditional way of solving the problem is using bypass diodes. However, it is not efficient as the shadow can be very randomly and unevenly. This paper aims to study various types of interconnection of solar cells in a PV module in order to tackle the shading effect. Among all the interconnection schemes, three interconnections are focused in this paper, which are series parallel (SP), total cross tied (TCT) and bridge linked (BL). Additionally, this paper presents a methodology to study the performance of different interconnection PV panels under partial shading condition. Three PV panels were constructed and various partial shading patterns were modelled on it, the performance is then analysed through current-voltage curve and power-voltage curve. At the end of the paper, the result shows that different interconnection give different power output under different partial shadings. It is also concluded that TCT and BL configuration give significant improvements as compared to SP configuration on power output under partial shading condition.

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LIST OF SYMBOLS / ABBREVIATIONS

V	voltage, V
I	current, A
P	power, W
V_{oc}	open circuit voltage
I_{sc}	short circuit current
V_{mp}	maximum power voltage
I_{sc}	maximum power current
R_s	series resistance
R_{sh}	shunt resistance
Ω	ohm
PV	photovoltaic
c-Si	crystalline silicone
FF	fill factor
MPP	maximum power point
NOCT	nominal operating cell temperature
LCD	liquid crystal display
SS	simple series
SP	series parallel
TCT	total cross tied
BL	bridge linked
HC	honey comb

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CHAPTER 1

INTRODUCTION

1.1 Background and Problem Statement

In the past few years, the world used to rely heavily on fossil fuel to generate electricity to meet the fast growing demand. Fossil fuels are non-renewable energy and this non-renewable energy will eventually dwindle and becoming too expensive to be harnessed. Moreover, fossil fuels is also one of the main causes of air pollution such as greenhouse effect, acid rain, global warming and more, bringing tons of bad drawbacks to the environment. In recent years, the rapid depletion of fossil fuel at an alarming rate as well as the growing concern of the environmental issue has driven the world towards employing renewable energy. Renewable energy defined as the energy that comes from natural resources which naturally replenish such as solar, wind, water, geothermal heat and etc. Out of all this renewable energies, most of them are comes from the Sun energy either directly or indirectly.

The sunlight, also known as solar energy is nearly the source of all the energies on earth. For example, the wind energy is harnessed from the air currents that flows between two regions with a different temperature that caused by solar heat. Biomass, an organic matter that stored energy through photosynthesis which its energy can then be used for heating or other purposes. Even hydro energy is derived from the Sun as we know from the hydrologic cycle. The solar energy is categorized into active solar or passive solar by depending on the way how the solar energy is captured (Conserve Energy Future, 2009). Active solar used special equipment to convert solar energy into heat and electric power including photovoltaic (PV) technologies, concentrated solar

power and also solar water heating. On the other hand, passive solar takes the advantage of the existing heat from Sun. Some solar passive techniques include orientation of a building with respect to the Sun, selecting materials with favourable thermal mass or light dispersing properties (Elza and János, 2008).

In recent year, solar energy is getting more attention from the scientist, researchers and also social community to overcome the environmental issues as well as the fast-growing energy demand. This is because solar energy is an abundant source at cost free and it is environmentally friendly. A solar cell or photovoltaic (PV) cell is used to harness the solar energy. It is an electronic device that is able to directly convert solar irradiance into electricity. It has becoming one of the promising solutions as there is improvisation in semiconductor technology and the advancement in power conversion technology over the years (Mutoh, Ohno and Inoue, 2008). Due to the same reasons, the price of PV cell had been greatly reduced and becoming more commercial.

A single PV cell is not enough to generate sufficient voltage and current for daily commercial use. Thus, many PV cells are interconnected and encapsulated to make a PV module. These PV cells are connected together to form an array of both series and parallel to generate the desired output voltage and current. If the solar cells in the module receive different levels of solar irradiance, mismatch of those cells will happen (Wang and Hsu, 2011). A PV module power output is nonlinear and will reduce notably if solar cell mismatch happen since solar cell has nonlinear characteristic. One of the major factors that cause the mismatch is the shading of one part of the PV module, also known as partial shading. The shaded solar cell will absorb the power generated from the unshaded cell and cause localize heat that will eventually breakdown the PV module (Petrone and Ramos-Paja, 2011).

In order to solve this problem, conventional PV modules will have bypass diodes connected in the array of solar cells. In a conventional solar module, solar cells are connected as a string in series to meet the desired output voltage, and then these strings are connected in parallel to meet the current output. It will have three bypass diodes connected in between of two strings so that if any of the strings is shaded, the current can be bypass and minimize the power losses. However, bypass diode may also

cause the PV module to drop more power output even only a few cells are shaded since the shading is random and uncertain (Bulanyi and Zhang, 2014).

Thus, this project aims to study other possible interconnection of solar cells within the solar module so that it can tackle partial shading more effectively and thus generating more power under various kind of shading condition. It is well aware that various interconnection schemes had been studied by other researchers or engineers. However, most of their research are focus on an upper level, which is the interconnection between solar modules for PV array in a solar power plant. Different from their project, this project will be done at a lower level at the solar cell within the solar module which is still rarely done by other engineers. Imagine, if the maximum power output of a single PV module can be increased by several percentage, now to what extend the power can be yield from a PV power plant in a year.

1.2 Aims and Objectives

The main aim of the project is to study various possible interconnections of solar cells in the solar module. A different types of interconnection of solar cells can effectively tackle the shading loss or power mismatch loss of the PV module under different environment condition. This project includes hardware simulation and experiment to obtain an accurate and precise result.

As such, the objectives of this project are:

- To study various possible interconnection of solar cells for a solar panel.
- To construct a prototype of solar panels with different interconnection schemes.
- To study the characteristic and performance of different interconnection solar panel under partial shading conditions.

1.3 Scope

There are a lot of different PV cell available on the market, however, the scope of this project will only focus on the crystalline silicon (c-Si) type of solar cell. The scope of this project involves the research of various existing interconnection of solar cells and understand how shading problem can affect the maximum power output of the PV module. The project scope focuses mainly on three interconnections which are series parallel, total cross tied and bridge link. In addition, this project will not focus on the effect caused by bypass diode, the number of bypass diode involves in this project will be three per modules. In chapter two, the literature review will study the different type of possible shading and how it is going to affect the power output of each PV module with different interconnection. The solar cell characteristic and operation, as well as the module configurations, also presented in the literature review. In addition, this project also includes a self-developed and designed IV tracer and data logger. The prototype of PV modules will also be constructed to study the power output variations under different circumstances of environment. At the end of the project, the results obtained from the experiment is compared and analysed to determine and investigate the interconnection configuration with highest performance under partial shading.

CHAPTER 2

LITERATURE REVIEW

2.1 Solar Cell

A solar cell is an electronic device that made from semiconductor materials which having a p-n junction and is able to convert solar irradiance into electricity. The process of converting the solar irradiance into electricity is known as photovoltaic effect. When a sunlight is striking on the cell, the electrons gain more energy and thus jump to higher energy level. The electrons are now free to move, leaving the holes in the materials free to move too. When an external load is connected, the electron will flow out of the semiconductor through the top contact. On the other hand, the holes flow through the bottom of the cell, expecting the arrival of electrons from the top to complete the circuit. The flow of electrons is the flow of current, and the voltage is from the internal electric field at the p-n junction. Thus, power is generated from the solar cell when exposed to light.

2.1.1 Electrical Characteristic

2.1.1.1 Equivalent Circuit Model

Figure 2.1 shows the equivalent solar cell circuit model. Noted that the circuit consists of a series resistance, R_s and a shunt resistance, R_{sh} . R_s represents the resistances at the metal-semiconductor interface as well as the ohmic losses in the front contacts of the

solar cell. While, R_{sh} represents the leak current of solar cell and it can cause significant power losses. The reason of this is that R_{sh} will provide an alternate path for the light-generated current to flow through which in turn result in low voltage develop in solar cell and finally reducing the power. The voltage-current characteristic of the solar cell can be expressed as:

$$I = I_{ph} - I_{o1} \left[\exp \left(\frac{(qV + IR_s)}{AK_b T_k} \right) - 1 \right] - \frac{(V + IR_s)}{R_{sh}}$$

where

I = output current

I_o = diode current

$I_{ph} = I_{sc}$ = photon current

T_k = operating temperature

A = diode ideality factor

q = electron charge constant (1.602×10^{-19} C)

K_b = Boltzmann constant

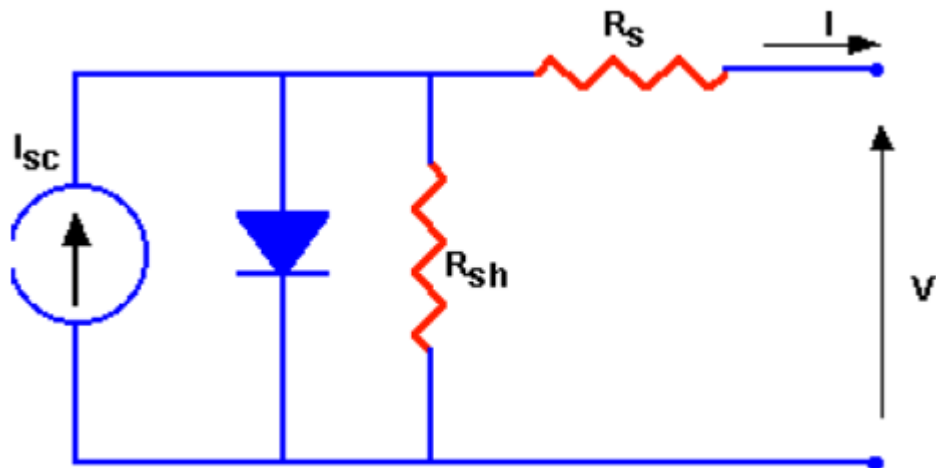


Figure 2.1: Solar Cell Circuit Model

2.1.1.2 Open Circuit Voltage and Short Circuit Current

When the resistance is infinite, the voltage across the cell will be at its maximum, known as the open circuit voltage, V_{oc} . The current in the cell at this time will be zero. Next, the short circuit current, I_{sc} is the current that flow through the solar cell when the resistance is zero, the cell is in short-circuited (Shukla, 2010). There will be zero voltage across solar cell at this time and the current will reach its maximum. For an ideal case, the short-circuit current is equal to the maximum current that can be drawn from a solar cell. There are several factors that can affect the value of short-circuit current. These include the area of the solar cell, the spectrum of incident light, the light intensity, optical properties and also the collection probability of the solar cell. For most of the case, the spectrum of light is standardise to AM1.5 and the solar cell area is also fixed in a solar module. The intensity of the light is similar to the number of photons available in the light or in this case, the level of solar irradiance. The relationship between I_{sc} and solar irradiance is directly proportional.

2.1.1.3 Maximum Power Point (MPP)

The current-voltage characteristics of a solar cell can be studied by connecting a variable resistance to the cell as load. By varying the load resistance between minimum to maximum, the current and voltage values will vary as shown in Figure 2.2. The red line will be the I-V curve while the black line is the power curve. The power output at V_{oc} and I_{sc} will be zero since it will be 1 parameter equals to zero when another is at maximum. Between these 2 points, the power curve rises and fall and there is a maximum power point which indicates the maximum power output of the cell.

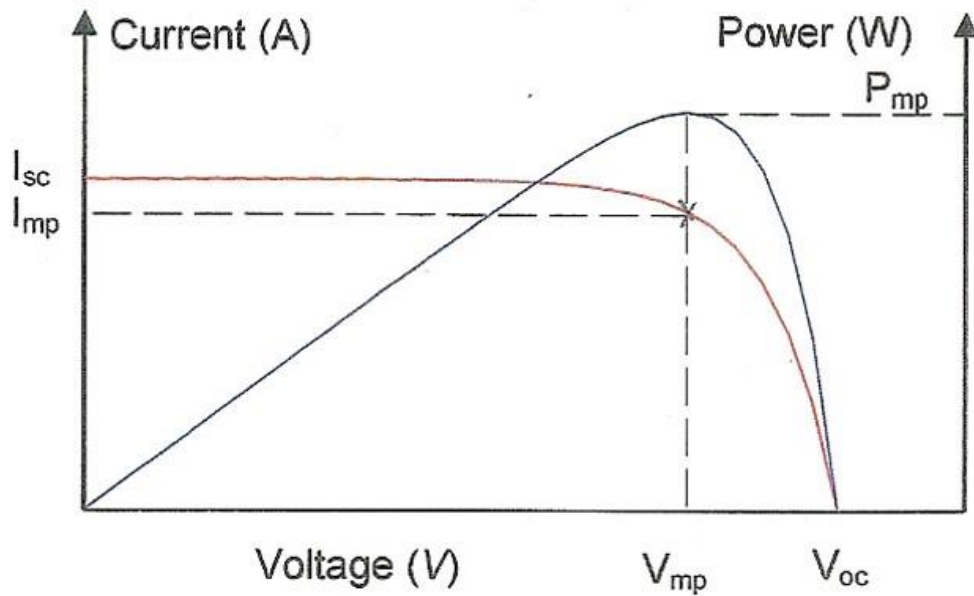


Figure 2.2: Power Curve of Solar Cell

The generation of power in solar cell is the product of voltage and current, $P = IV$. P is zero when either I or V are zero, which occurs at V_{oc} and I_{sc} respectively. When $V = V_{mp}$ and $I = I_{mp}$, the maximum power, P_{mp} is produced, this point is known as maximum power point (MPP) (Berning, 2011). It is essential to make sure a solar cell is always operating at MPP or near to it so that maximum power is obtained.

2.1.1.4 Fill Factor (FF)

The V_{oc} and I_{sc} are the maximum voltage and current that possible to generate from a solar cell. As a result, the product of V_{oc} I_{sc} is the desirable goal in delivering power for solar cell. However since this is not possible, fill factor (FF) is a more commonly use parameter to represent the maximum power from a solar cell. FF is explained as the ratio of maximum output power to the product of V_{oc} and I_{sc} . $FF = (V_{mp} I_{mp}) / (V_{oc} I_{sc})$. As seen from Figure 2.2, FF measure the closeness of the solar cell I-V curve to the rectangular shape. FF can also be considered as the measure of quality of a cell, a typical FF values are in the range of 7.0 to 8.5.

2.1.2 Factors Affecting Solar Cell Performance

2.1.2.1 Temperature Effect

Solar cell is very sensitive to the temperature, like all others semiconductor do. The increase in temperature will cause changes in most of the semiconductor parameters as it decreases its band gap. The output voltage and efficiency of a solar cell increase with the decrease of temperature. From the Figure 2.3, it is obvious that V_{oc} decrease as the solar cell temperature increases. However, I_{sc} increase insignificantly. The combined effect is the reduction of the maximum power output. Typically, the voltage will have approximately 0.5% changes for every 1°C variation in temperature, so does the power output.

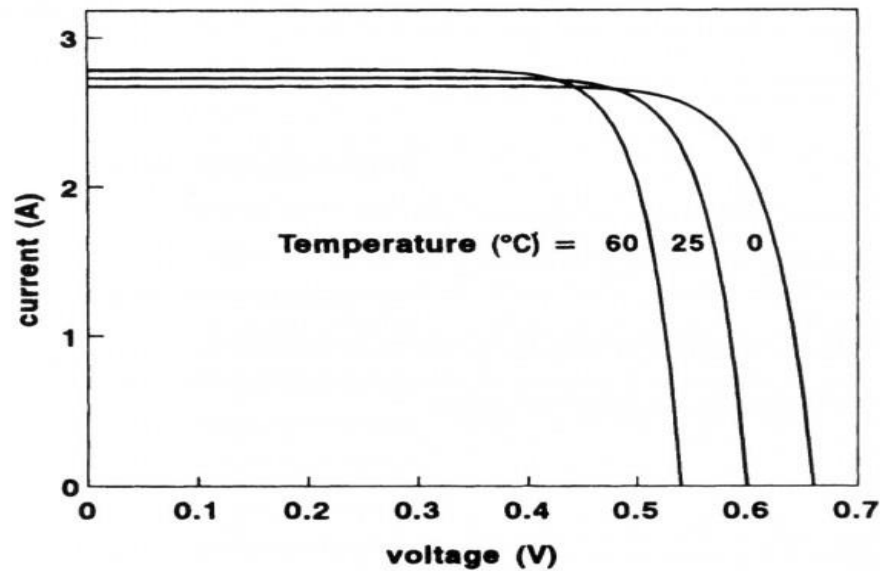


Figure 2.3: I-V Curve with Temperature Effect

The solar cell is normally rated at the temperature of 25°C . However, the temperature is normally higher than the ambient temperature and hence higher than the standard test cell temperature of 25°C . Nominal operating cell temperature (NOCT) gives better indication of the expected operating cell temperature. NOCT is defined as the temperature reach when following conditions are met:

Irradiance = 800 W / m^2

Ambient temperature = 20°C

Wind velocity = 1 m / s

The typical NOCT for c-Si is in the range of $45 - 50^\circ\text{C}$.

2.1.2.2 Irradiance Effect

Another factor that will affect the solar cell efficiency will be the level of sun irradiance. The I_{sc} had almost linear variation with the level of irradiance, but the V_{oc} only change slightly. Figure 2.4 shows the I_{sc} increase as the irradiance increase, V_{oc} does not increase dramatically. The graph is also assuming the temperature is at constant and not affected by the change of irradiance.

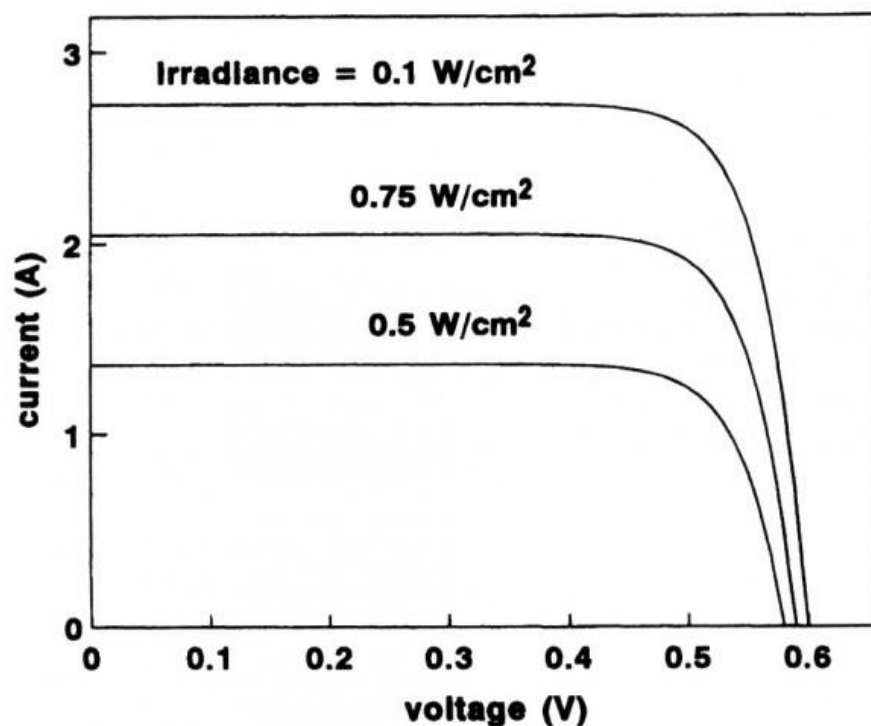


Figure 2.4: I-V Curve with Irradiance Effect

2.2 Solar Module

In order to achieve desired voltage and current output, solar cells are interconnected in both series and parallel to form a PV panel, also known as solar module. Typically, a solar module consists of 36 solar cells connected in both series and parallel (Guo, et al., 2012). A PV module will consist of several bypass diodes as additional components other than solar cells. The roles of bypass diode in the PV module will be explained in the section below. Different types of interconnection between the solar cells will result in different efficiency of PV module under partial shading condition.

2.2.1 Series Connection

If all the solar cells are connected in series in a module, the total voltage output of the module will be the sum of each individual cell voltage while the output current will be the same with every cell in the module.

$$V = V_1 + V_2 + V_3$$

$$I = I_1 = I_2 = I_3$$

where V = total voltage and I = total current.

When one of the cells in the series connection is shaded, the irradiance that experience by that particular cell is reduced, thus decreasing the current output. At the same time, the other unshaded cell will press their current through the shaded cell. Assuming that the cell is being shaded by three-quarters, the current will also drop by three-quarters. Consequently, the MPP of the module will also reduce by three-quarter even there is only one cell being shaded in the whole module. Since the irradiance level will not alter the voltage greatly, the MPP of the module is almost completely subject to the shaded cell.

2.2.2 Parallel Connection

With all the solar cells connect in parallel connection in a solar module, all the cells will share the same voltage value. The output current of the module is the sum of each individual current output from the solar cell, exactly opposite as series connection.

$$V = V_1 = V_2 = V_3$$

$$I = I_1 + I_2 + I_3$$

When the same scenario as above takes place on a module with all the solar cells are parallel connected, the MPP output is reduced but not as much as in series connection. This is because in parallel connection, the current add up to give the total current output of the module rather than sharing the same current output as in series. However, it is not practical to have a module with all the solar cells connected in parallel only because then the V_{oc} will have a very small value at around 0.6 V only. Furthermore, the current will be extremely high and a very thick cable is needed for power transmission.

2.3 Shading

2.3.1 Shading Category

Shade is simply defined as the blocking of sunlight either directly or indirectly by an object, and so the shadow is formed. Shading can be caused by any objects such as cloud, leaves, roof and etc. as the result, there can be various types of shading with different size and shape, linear or non-linear cause by natural environment. A small shadow may cover a single solar cell in the PV module, but a bigger shadow may cover the entire string in the module or even the entire module itself. It can be classified into two major groups of objective shading and subjective shading (Bulanyi and Zhang, 2014).

An objective shading is formed by the weather during cloudy day or heavy pollution environment such as haze. This type of shading reduces the overall sunlight intensity received by the PV panel. Subjective shading is caused by a solid shade shape which is the result of an object blocking the sunlight to the PV panel. It is clear that objective shading can hardly be avoided due to the natural phenomena. However, subjective shading can be greatly improved with better design and maintenance service carried out.

From subjective shading, it can be further divided into two groups which are static shading and dynamic shading. As it comes from the name, static shading is fixed throughout the day and will not affect by the sun angle. Static shade address to the shade that cause by a very close blockage that typically stick on PV panel's glass such as leaves, dirt or bird droppings. On the other hand, the shading that is affected by the shadow due to sun is known as dynamic shading and it depends on the sun angle. For example, the shadow of buildings, trees, roof and any other objects that form shadow on the PV panels.

In order to refer how much a PV module is being shaded, whole shading and partial shading were used to describe the ratio of cell shading which the formula is, shaded area / total cell area. The whole shading indicates that the cell is below the threshold point to generate cell voltage due to the insufficient of irradiance while partial shading indicates that the cell is above the threshold point and is able to generate cell current with sufficient irradiance. Whole shading and partial shading will give rise to impact on module voltage output and current output and thus affect the total maximum power output.

2.3.2 Shading Effect on PV Module

As solar cell is a semiconductor that produces electric power directly from photon, the power output of it will be greatly affected by the intensity of light or the Sun irradiance level. When the solar module is shaded, it start to consume power and works like a

load. From a solar module IV curve and PV curve, the shading effect on a solar cell can be seen clearly.

There are mainly two main properties that can be observed, which are the reduction of the total maximum power output and the present of multiple peaks in the PV curve which also known as local maxima point. The cause of total power output reduction will be the lower level of irradiance level which may be due to weather condition. The reason that causes multiple peaks will be the operation of bypass diode (Picault, et al., 2010).

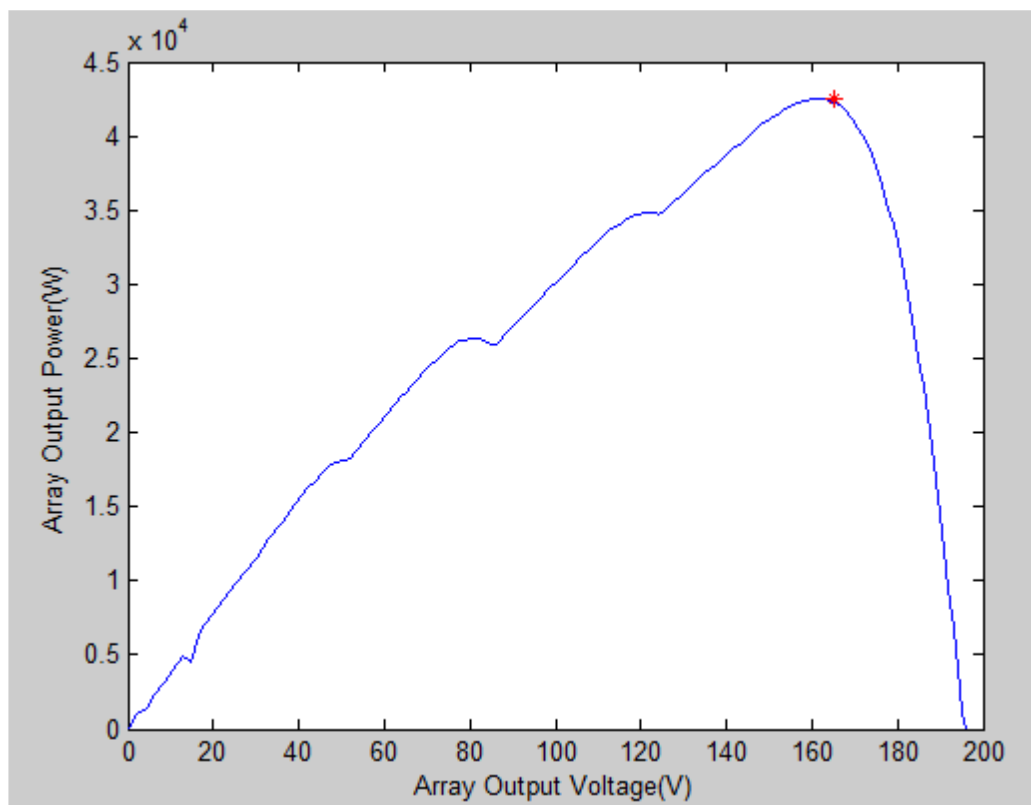


Figure 2.5: PV Curve Showing Multiple Peak (Pachpande and Zope, 2012)

Figure 2.5 shows multiple local maxima points and a global maximum point that marks with a red dot. Notice that the curve looks like a staircase with those steps. This is due to the operation of bypass diodes as every step in the curve represent the activation of each bypass diode. Further explanation on the working operation of bypass diode will be cover in the next section. With multiple local maxima point, the conventional algorithm that used by the inverter to determine maximum power point

cannot be used anymore. The reason of it is that the algorithm will stop when it got the first maximum point and though it was the MPP for the working solar cell.

2.4 Bypass Diode

Typically, bypass diodes are install in a solar module to get rid of the power mismatch losses during partial shading. The bypass diode is connected in parallel to the solar cell strings with opposite polarity such that it is reverse biased during normal operation. When there is no shading on the solar cells, all the solar cells will have positive voltage output and this voltage act as a reverse voltage for the diode. During this point, the diode will not conduct any current and act like an open circuit. On the other hand, when one of the solar cells is shaded and has a negative voltage, the bypass diode become forward bias, providing alternating path for the current to flow through.

As the bypass diode is in forward biased, it shunts away the module current, preventing the current to force through the shaded cell. In addition, this also effectively prevent the formation of hotspots in the solar module. Hotspots heating happens when one of the solar cells is shaded and generating low current output. Assuming the PV module is short circuited, then the power generated by all the other solar cells will be press through the shaded cell. A large power dissipation happens at a small area give rise to local overheating or the formation of hotspots.

Although the bypass diode works perfectly with the solar cell when shaded, but it is not cost effective to have a bypass diode across each cell. Instead, the solar cells are normally group into sub-string and a bypass diode is used per sub-string. Figure 2.6 show the IV curve of a solar module with a different number of bypass diode. As discussed, bypass diode can prevent power mismatch. Thus the more numbers of bypass diode install, the higher the performance of a solar module can achieve.

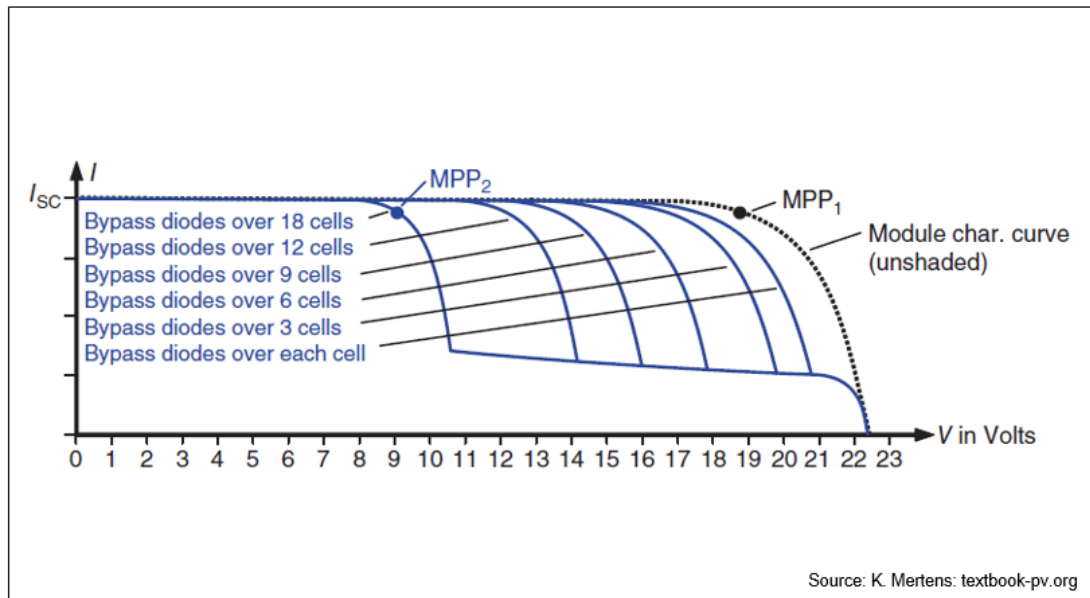


Figure 2.6: IV Curve with Different Number of Bypass Diodes

Additionally, bypass diode may not always perform as expected. For example, assuming a PV module with 60 cells as shown in Figure 2.7.

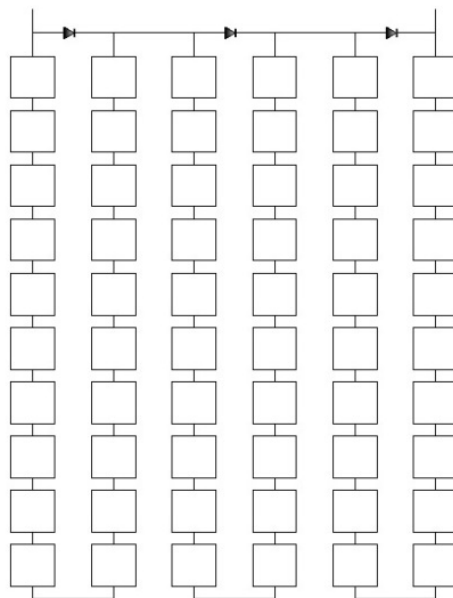


Figure 2.7: PV Module with 60 Solar Cells and 3 Bypass Diodes

Referring to Figure 2.7, if one of the solar cell in the first sub-string is whole shaded, then it corresponds bypass diode will become active and module output power

will drop by $1/3$. Now, imagine if subjective shading happens to shade all the six solar cells at the bottom row. This will lead to the activation of all bypass diodes and eventually leads zero output, disabling the PV module.

Since bypass diodes alone is not sufficient to solve the partial shading losses problem perfectly, new interconnection of solar cells is studied to increase the PV module efficiency under various shading condition.

2.5 Various Interconnection of PV Cell and PV Module

As shadow problem or partial shading is the major problem encounter by PV module, many research had been done to minimize this power degradation caused by mismatch losses. In a paper by Narendra, D.K. and Nalin, K.G., 2003, a simulation model was used to investigate the electrical characteristic of PV array interconnection schemes. Two modular arrays with the size of 6×6 and 9×4 have been considered. The maximum power and fill factors for this array have been obtained by the simulation models and the result was given in Table 2.1 and Table 2.2. The paper draws the conclusion that cross-tied configurations, which include TCT and BL, has higher maximum power significantly when shadowed occurs.

Table 2.1: Maximum Power and Fill Factor For 9×4 Arrays

Ensemble	Maximum Power (W)			Fill Factor		
	BL	SP	TCT	BL	SP	TCT
Fresh Cells	35.04	34.78	34.66	0.73	0.73	0.73
Soiled Cells	8.85	8.14	8.57	0.70	0.69	0.70

Table 2.2: Maximum Power and Fill Factor For 6×6 Arrays

Ensemble	Maximum Power (W)			Fill Factor		
	BL	SP	TCT	BL	SP	TCT
Fresh Cells	34.52	34.40	34.27	0.72	0.72	0.72
Soiled Cells	7.95	7.55	7.85	0.68	0.68	0.68

Besides, Wang, J.S. and Hsu, P.C., 2011, from National Yunlin University of Science and Technology had investigated on the partial shading of PV module with five different PV cell interconnection schemes. These five interconnection schemes are simple series (SS), SP, TCT, BL and honey comb (HC). In the paper, a random number generator was used to generate 36 different irradiance values to simulate the non-uniform solar irradiance that strikes on PV module and cause mismatch.

Table 2.3: Comparison of Peak Power and Fill Factor.

	Peak power (W)	Fill factor
SS	48.713	0.681
SP	48.807	0.69
TCT	49.248	0.677
BL	48.875	0.678
HC	49.081	0.68

The results from this paper show that TCT configuration has the highest value in terms of power, follow by HC and BL while SP has the highest fill factor. The analytical method used in the paper is based on nonlinear IV characteristic, Kirchhoff's Voltage Law and Kirchhoff's Current Law which is then solved by Newton-Raphson algorithm.

CHAPTER 3

METHODOLOGY

3.1 Overview

In this chapter, the method of study and implementation will be clarify and explain. The main focus for this project is to study the different type of shading effect on the solar cell operation and thus implement various interconnections of solar cells to increase the efficiency of the PV panel. The methodology of the project is summarized and presented as shown in Figure 3.1. The rough idea of each individual process block will be explained below while the details of it will be discuss in several sub chapter.

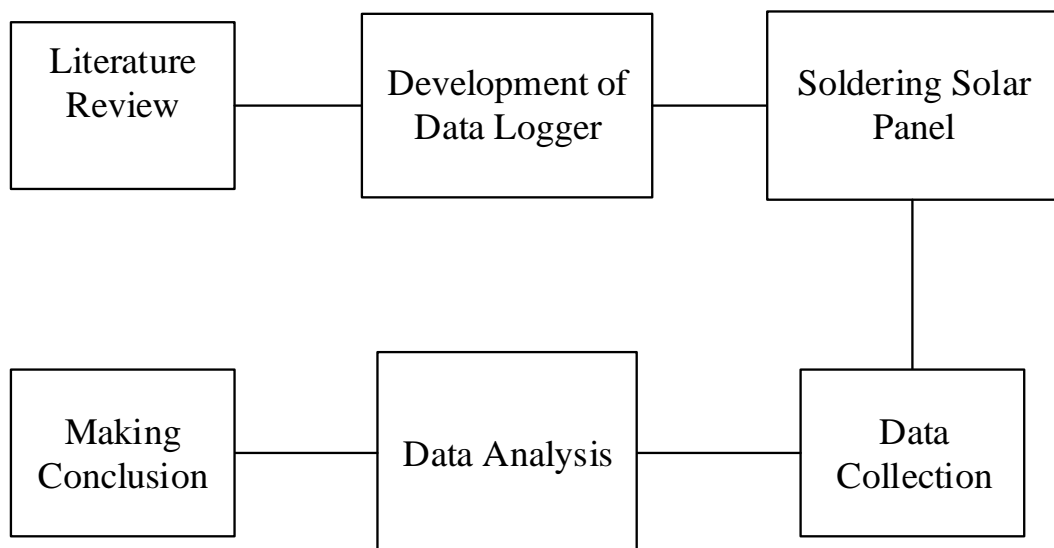


Figure 3.1: Flowchart of the Project

At the early stage of the project, literature review is done to gain information and identify similar work that had been done by others engineer within the same area. In addition, it allows me to compare and critique previous findings as so to suggest further studies. All the information obtained for this project is from article, journal, conference paper, textbook, internet, advice from senior engineers and guideline from lecturer.

After the information gathered is sufficient and studied, the project move on to the next stage which is the developing of data logger. The data logger are used to collect data from the solar panels and record it directly into a SD card. The data recorded are voltage, current and power. This data logger can be achieved by using an Arduino Mega 2560 together with an Adafruit data logging shield. The details of the data logger will be discuss further at section 3.2.

Next, the project continues to construct solar panel with three different interconnection schemes. Three solar panels are constructed with different solar cell interconnection schemes. The type of solar cell used is presented as in section 3.3.2 and the details for each solar cell interconnection schemes is discuss in section 3.3.1.

The initial planning for the data collection is by using the data logger constructed with Arduino. However, this data logger is not used at the end due to some limitations which will be further discuss later. The data collection is then achieved by using PVPM1000CX I-V-Curve tracer. To collect data, each of the solar panel is exposed to the sunlight. The data are first collect under no shading condition, then different type of possible shading condition were carried out to study the effects of it on each of the solar panel. Hence, the impact for different type of shading on solar panel was experimented in this stage by analysing the data collected. Additionally, total power output from different solar panel with different interconnection schemes are be studied and data analysis are be carried out. Section 3.4 will explain how the data been collect and which type of shading is model in details.

3.2 Data Logger

The data logger is served to log the required data directly from the solar panel into a SD card instead. This can save a lot of time as compared to recording data by using hand. The data logger comprise of several components which are Arduino Mega 2560, Adafruit data logging shield, 16×2 LCD, button, SD card, ACS712 Hall Effect current sensor, potentiometers and resistors. The selection of the components for the data logger plays an important roles to make sure the data logger can function properly as expected and able to log the output from solar panel correctly into the SD card. Selecting appropriate components with reasonable price is also important to ensure the total cost of the entire project is within budget.

3.2.1 Arduino Mega 2560

According to the Arduino official website, Arduino is an open-source electronics platform that based on easy to us software and hardware. An Arduino board is aim to provides a simple microcontroller kit that is able to interact with the user easily. With multiple sensors as the input, it allows Arduino board to control the physical world surrounding.

In this experiment, Arduino Mega 2560 as shown in Figure 3.2 is used. Arduino Mega 2560 is an ATmega2560 microcontroller based circuit board with the dimension of $101.52 \text{ mm} \times 53.3 \text{ mm}$. It has 54 digital I/O pins, 16 analog inputs, 4 UARTs, a 16MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. Table 3.1 shows the specification of Arduino Mega 2560.

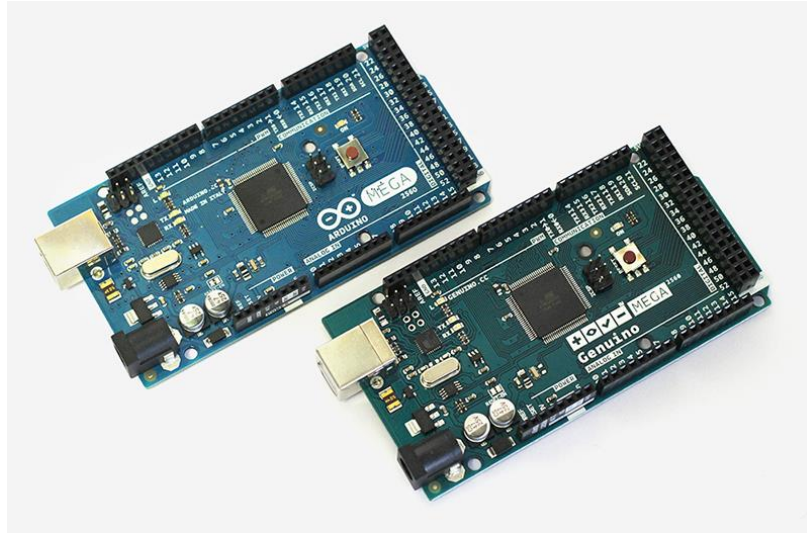


Figure 3.2: Arduino Mega 2560

Table 3.1: Specification of Arduino Mega 2560

Microcontroller	ATmega2560
Operating Voltage	5 V
Input Voltage (recommended)	7-12 V
Input Voltage (limit)	6-20 V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz
Length	101.52 mm
Width	53.3 mm
Weight	37 g

3.2.2 Adafruit Data Logging Shield

Since the Arduino Mega itself is incapable of data logging, an external shield is needed to allow the data being store into a SD card. This data logging shield allow saving data files on any FAT16 or FAT32 formatted SD card. In addition, the shield also included real time clock (RTC) which allow the time clock to keep running even if the Arduino is unplugged and no power. With the RTC, the data recorded can be timestamp accurately and precisely. Most importantly it helps saving a lot of unnecessary work as the time remain correctly and do not need to be reset every time after the power is off and on again. Figure 3.3 shows the Adafruit data logging shield.

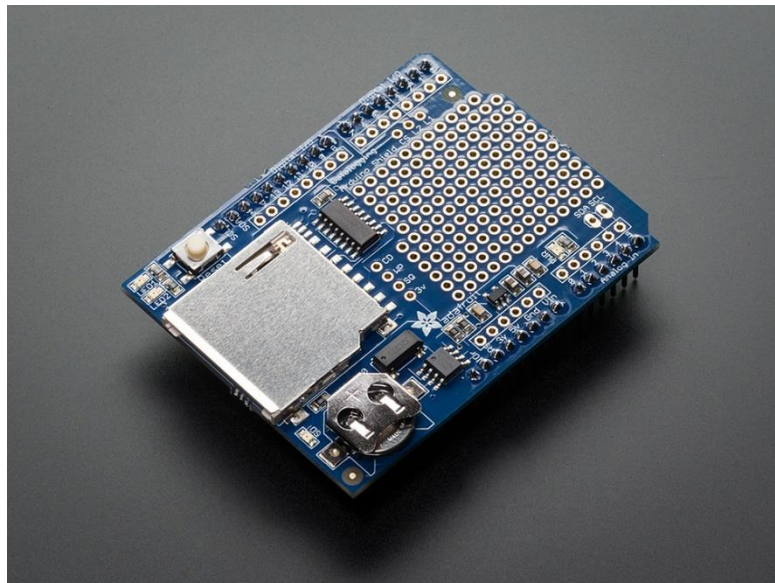


Figure 3.3: Adafruit Data Logging Shield

3.2.3 ACS712 Hall Effect Current Sensor

The ACS712 is a precise and economical current sensing device which is based on the principle of Hall-effect. This current sensor is able to sense both AC and DC current. The principle of Hall-effect state that when a current carrying conductor is placed into a magnetic field, voltage will be generated perpendicular to the direction of current and magnetic field. In the sensor, it consists of a precise linear Hall circuit with a copper conduction which the applied current will pass through. A magnetic field is

then generated and being convert into proportional voltage by the Hall IC when current applied. Figure 3.4 shows the ACS 712 current sensor and Table 3.2 shows the specification of the sensor which is extracted from the datasheet.

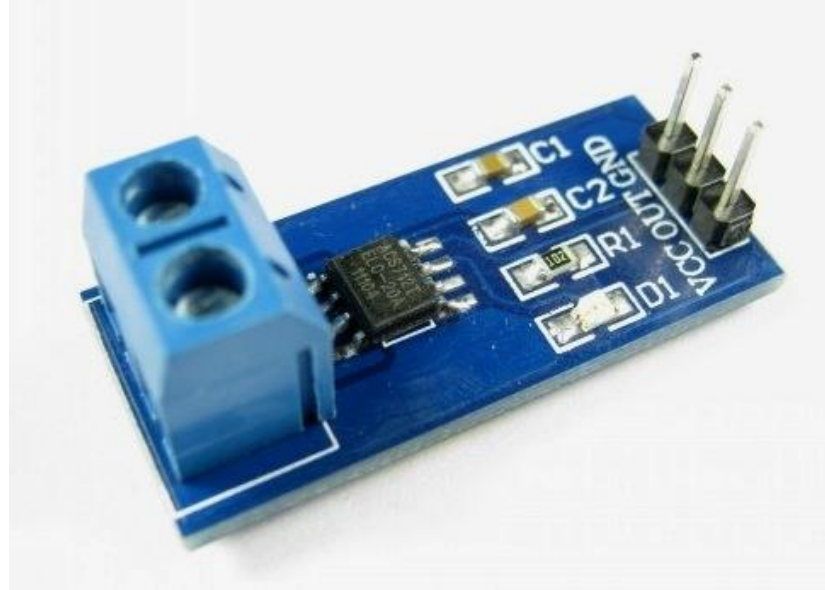


Figure 3.4: ACS 712 Hall Effect Current Sensor

Table 3.2: Part of Specification of ACS712

Characteristic	Symbol	Test Conditions	Min.	Typ.	Max.	Units
ELECTRICAL CHARACTERISTICS						
Supply Voltage	V_{CC}		4.5	5.0	5.5	V
Supply Current	I_{CC}	$V_{CC} = 5.0$ V, output open	–	10	13	mA
Output Capacitance Load	C_{LOAD}	VIOU to GND	–	–	10	nF
Output Resistive Load	R_{LOAD}	VIOU to GND	4.7	–	–	k Ω
Primary Conductor Resistance	$R_{PRIMARY}$	$T_A = 25^\circ\text{C}$	–	1.2	–	m Ω
Rise Time	t_r	$I_P = I_P(\text{max})$, $T_A = 25^\circ\text{C}$, $C_{OUT} = \text{open}$	–	3.5	–	μs
Frequency Bandwidth	f	–3 dB, $T_A = 25^\circ\text{C}$; I_P is 10 A peak-to-peak	–	80	–	kHz
Nonlinearity	E_{LIN}	Over full range of I_P	–	1.5	–	%
Symmetry	E_{SYM}	Over full range of I_P	98	100	102	%
Zero Current Output Voltage	$V_{IOUT(Q)}$	Bidirectional; $I_P = 0$ A, $T_A = 25^\circ\text{C}$	–	$V_{CC} \times 0.5$	–	V
Power-On Time	t_{PO}	Output reaches 90% of steady-state level, $T_J = 25^\circ\text{C}$, 20 A present on leadframe	–	35	–	μs
Magnetic Coupling ²			–	12	–	G/A
Internal Filter Resistance ³	$R_{F(INT)}$			1.7		k Ω

3.3 Soldering Solar Panel

In this stage, several solar cells interconnection schemes that had been studied were constructed to begin with the experiment. The solar cell interconnection schemes that

constructed includes series-parallel (SP), total cross tied (TCT) and bridge linked (BL). As it is impossible to vary and change the interconnection of solar cells within an existing PV panel, new PV panel was constructed or developed. In this project, several small solar modules will play the role as solar cell and then being connect together to form a big solar panel. The solar module being used will be shown at section 3.3.2.

3.3.1 Interconnection Scheme

A SP connection is the most common used connection in a PV panel. It is the most simple connection scheme combining series and parallel connection. This type of connection is commonly used to meet the load power requirements (Deshkar, et al., 2015). However, from chapter two, we know that the connection scheme will gives significant power drop when subject to shading. Next, it will be the TCT connection. A TCT connection scheme is develop from the most basic SP connection by connecting ties across each row of junctions. In other words, solar cells in row are connected in parallel while solar cells in column are connected in series (Rani, Ilango and Nagamani, 2013). Lastly will be BL scheme which is the derivation from bridge rectifier pattern. Figure 3.5 shows all three interconnection schemes.

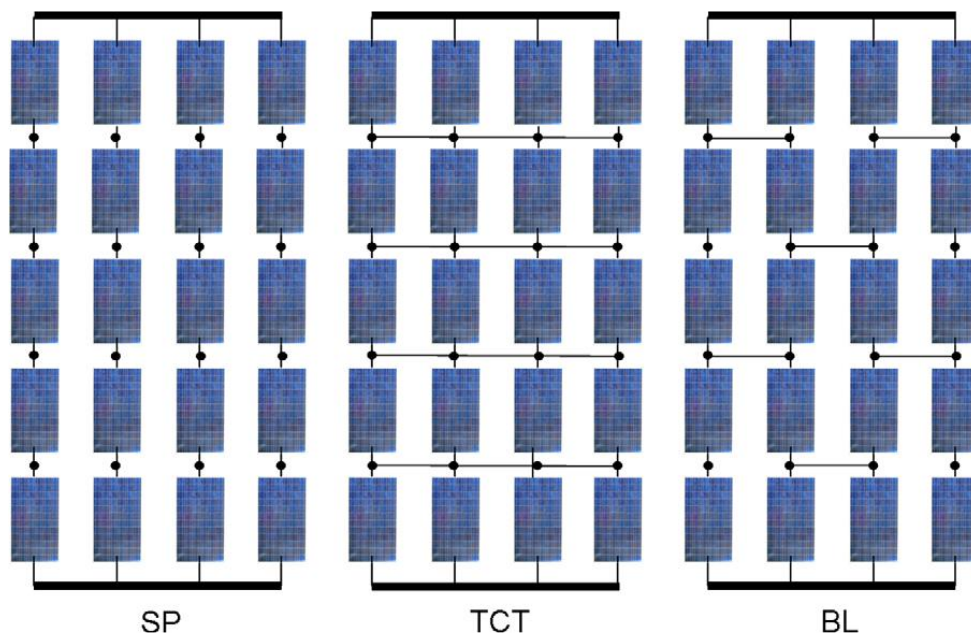


Figure 3.5: Diagram of SP, TCT and BL Interconnection Schemes

3.3.2 Solar Module

In the project, small solar module is used instead of raw solar cell. The reason for this is that raw solar cell is not economically available and difficult to be handle. Raw solar cell is normally being handle and connected by experience individual to avoid the risk of damaging the cell. The small solar module that plays the role as solar cell in this project is shown in the Figure 3.6 together with some its specification.

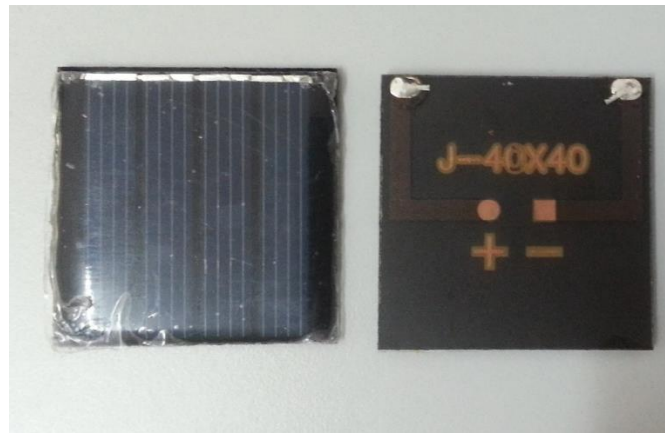


Figure 3.6: Solar Module

Table 3.3: Specification of the Solar Module

Maximum Power (P_{\max})	0.12 Wp
Voltage at Maximum Power (V_{mpp})	2 V
Current at Maximum Power (I_{mpp})	60 mA
Bypass Diode	0
Dimension	40 × 40 mm

3.4 Data Collection

The next stage of the project is the data collection which involves measuring several parameters such as V_{oc} , I_{sc} , V_{mp} , I_{mp} , power output and irradiance level. An ideal process of collecting data is to expose all three different interconnection scheme solar

panel side by side under the Sun at the same time so that they will have the data collected under the exact same environment condition, irradiance level for example. By doing so, we can save up a lot of time and effort while collecting data. Moreover, we know that the irradiance level vary very fast, thus the data also have to be collect in a very fast way before the irradiance level changes. In order to do that, a fast performance data logger is needed so that sufficient data can be collected within a small period of time.

As the result of that, the initial planning is to develop a data logger with Arduino as it supports multiple inputs and able to perform fast. Additionally, this also make sure the temperature remains unchanged as the data collection can be done in a short period of time. However, due to some of the limitation, the data logger is not use. Instead, PVPM1000CX I-V-Curve tracer was used for data logging.

The data was collected under several conditions in order to study the power output for different interconnection scheme solar panel. The constant variable in the experiment are irradiance level and temperature values while the manipulated variables are the different type of shading condition. Different type of shading scenario were carried out and model on all three solar panels. Cardboard was used to cover the solar panel to simulate the partial shading effects. Several partial shading scenario was performed such as shade horizontally, vertically, centre and etc. The data collection for each type of shading on each interconnection schemes is estimated to be carry out for 2 weeks. Multiple sets of data were obtained in order to get the average of the result so that it is more precisely accurate.

3.4.1 Shading Pattern

There are several shading pattern done on the solar panel in order to model and simulate all the possible shading that might happens. For example, a few solar cells at the centre is to model a bird drop, leaves or dust. A whole column or whole row shading is to simulate the shadow cause by nearby building or tree throughout the day. The shading conditions that had been done are as follow:

- a) 1, 2 and 3 columns shade, Figure 3.7 shows 2 columns shade.
- b) 1, 2, 3 and 4 rows shade.
- c) 4 solar cells in a column shade as shown in Figure 3.8.
- d) 2 solar cells in a row shade as shown in Figure 3.9.
- e) 2 solar cells in centre shade as shown in Figure 3.10.
- f) 8 solar cells in centre shade as shown in Figure 3.11.



Figure 3.7: 2 Columns Shade



Figure 3.8: 4 Solar Cells in a Column Shade



Figure 3.9: 2 Solar Cells in a Row Shade

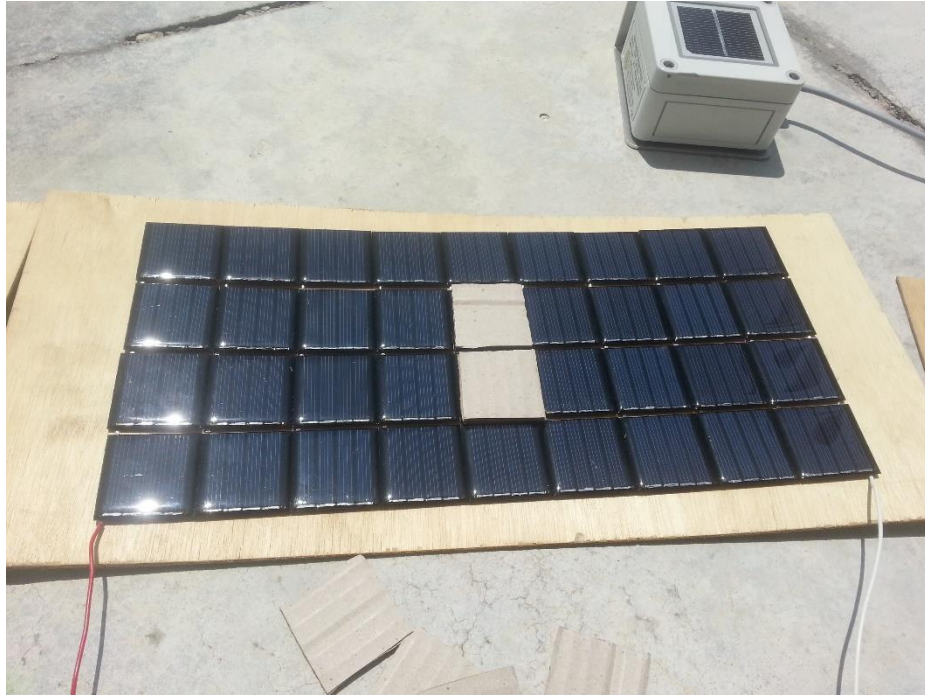


Figure 3.10: 2 Solar Cells in Centre Shade

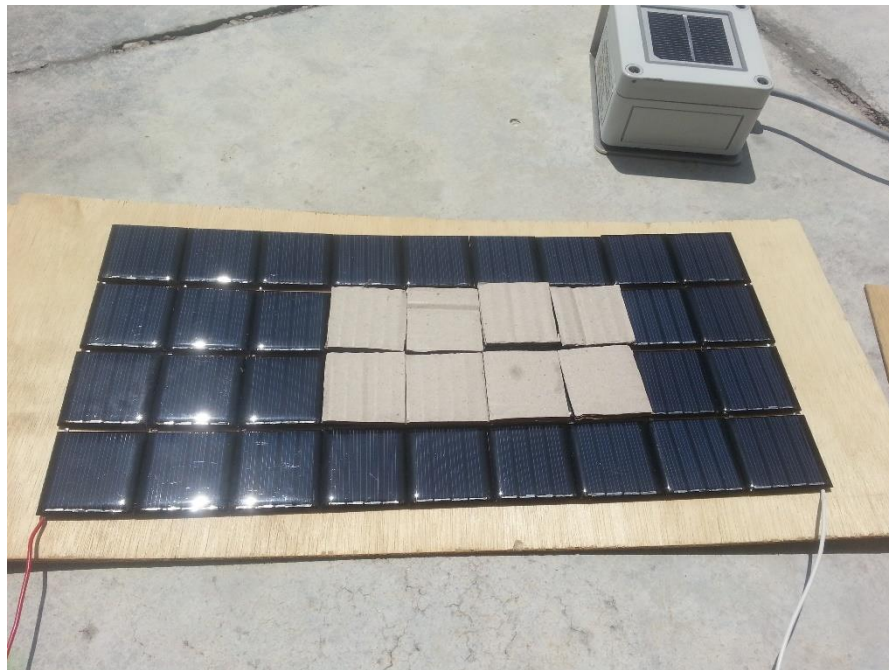


Figure 3.11: 8 Solar Cells in Centre Shade

3.4.2 PVPM1000CX I-V-Curve Tracer

The PVPM is a device manufactured by a German company known as PV-Engineering GmbH. The device is able to measure and trace the IV curve of solar module or strings. Additionally, the device can measure and calculate the peak power P_{pk} , the R_s and R_p from a single I-V-curve directly displaying the results and diagram on the internal graphical LC display.

The PVPM1000CX is a portable measuring device with integrated battery supply and battery charger in a durable and watertight plastic housing. The device can also function independently from other devices with its own industrial miniature PC and a high-contrast LCD TFT display. Moreover, it also allow data transfer to a computer over a standard USB interface. From PC, further analysis of the measured values can be done by using the compatible software installed. Figure 3.12 shows the PVPM1000CX and Figure 3.13 shows part of its specification.



Figure 3.12: PVPM1000CX

Measurement and Evaluation Unit:

Industrial class PC, Flash data storage 512MB (sufficient for several 1000 measurements)

No mechanically moved parts such as fixed disks, exhaust or similar

Sampling rate max. 100kHz, resolution 12Bit

Measuring accuracy for the I-V-characteristic better 1%, for the peak performance $\pm 5\%$

4-wire-measurement leads avoids systematic errors in voltage measurement

Measuring period single measurement 0.02 - 2 seconds (100 pairs of measured values)

Irradiation reference sensor (Phox) with integrated Pt1000 temperature sensor

Optional additional measurement of the back surface temperature of the module under test

Other commercially available irradiance reference sensors (i.e. ISET® sensor) can be used

Measuring Ranges	Voltage dc	Current dc	Temperature	Irradiance
PVPM1000CX	25 / 100 / 500 / 1000 V	2 / 5 / 10 / 20 A	-40°C - +120°C	0 - 1300 W/m2
PVPM1000CX40	25 / 100 / 500 / 1000 V	2 / 5 / 10 / 40 A	with Pt1000	(Standard Sensor)

The measuring ranges can be combined among each other

The measuring instrument automatically selects an optimal measuring range

The device must be used only for the test of current limited dc sources (photovoltaic generators)

Display

Daylight-suited colour-TFT display with LED back-light, resolution 480 x 272 pixels, high contrast

Operation

Menu driven by touch function of the display directly at the device

Operation and analysis alternatively with MS-Windows® application, communication over isolated USB

Voltage Supply

Lithium-Ion battery 11.25V/8.8Ah/99.6Wh (continuous operation about 8h)

External power supply with wide range input 90-264Vac, 47-63Hz, UL-approved, power 40W

Internal automatic battery charge controller with overloading protection

Display of the charge state over control LED at the front side of the housing

Continuous measurement possible during mains operation

Dimensions

Width: 40.6cm, height: 17.5cm, depth: 33cm, weight: about 7.7kg

Operating Conditions

	Temperature	Dampness
Operation	0°C to 50°C	10% to 90% (non-condensing)
Storage	-10°C to 85°C	5% to 95%

Figure 3.13: Part of Specification of PVPM1000CX

3.5 Data Analysis

With all the data available, analysis was then carried out to study the performance of each solar panel. From the data obtained, it is then used to plot IV curve and PV curve so that the operating characteristic can be seen clearly and the maximum power output point can be determined. From the graph, the working operation under partial shading for different interconnection scheme is discuss.

For an effective ways of analysing data, one of the interconnection schemes was set and use as the original reference so that the others two types of interconnection can be compare with it. As the SP interconnection scheme is most commonly used, it is set as the original references. By doing so, TCT and BL interconnection schemes performance can be easily compare by referring to this original references.

CHAPTER 4

IMPLEMENTATION

4.1 Solar Panel

As discussed in chapter 3, three solar panels were constructed with three different interconnection schemes which are Series Parallel, Total Cross Tied and Bridge Link as shown in Figure 4.2. Each of the solar panel is made up by 36 small solar modules with the configuration of 4×9 . The solar panel was being connected with tabbing wire, Figure 4.3. Figure 4.1 shows the front view of the solar panel.

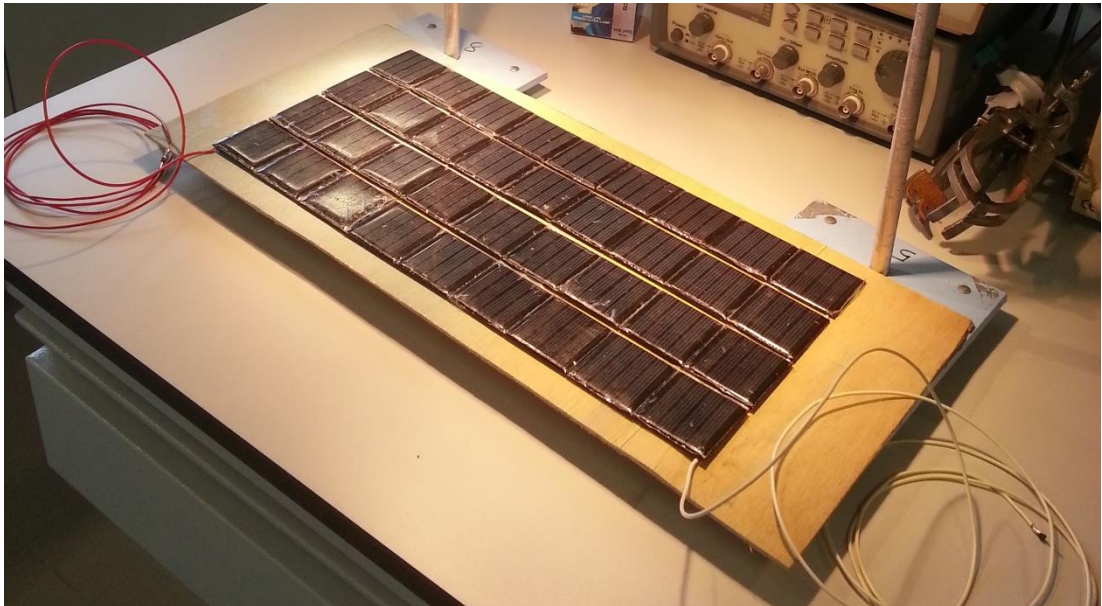


Figure 4.1: Front View of the Solar Panel

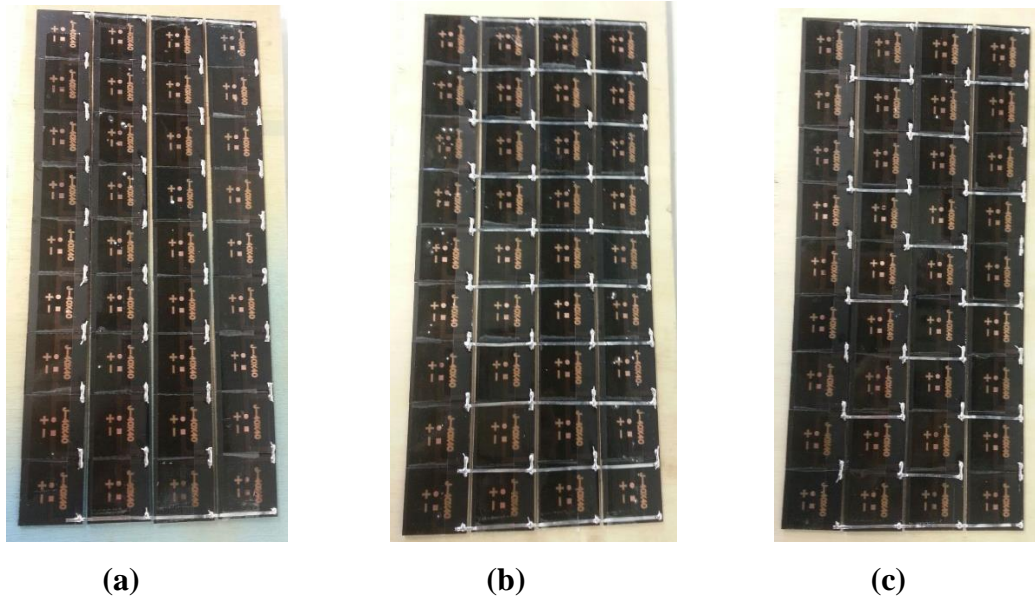


Figure 4.2: (a) Series Parallel, (b) Total-Cross-Tied, and (c) Bridge-Link

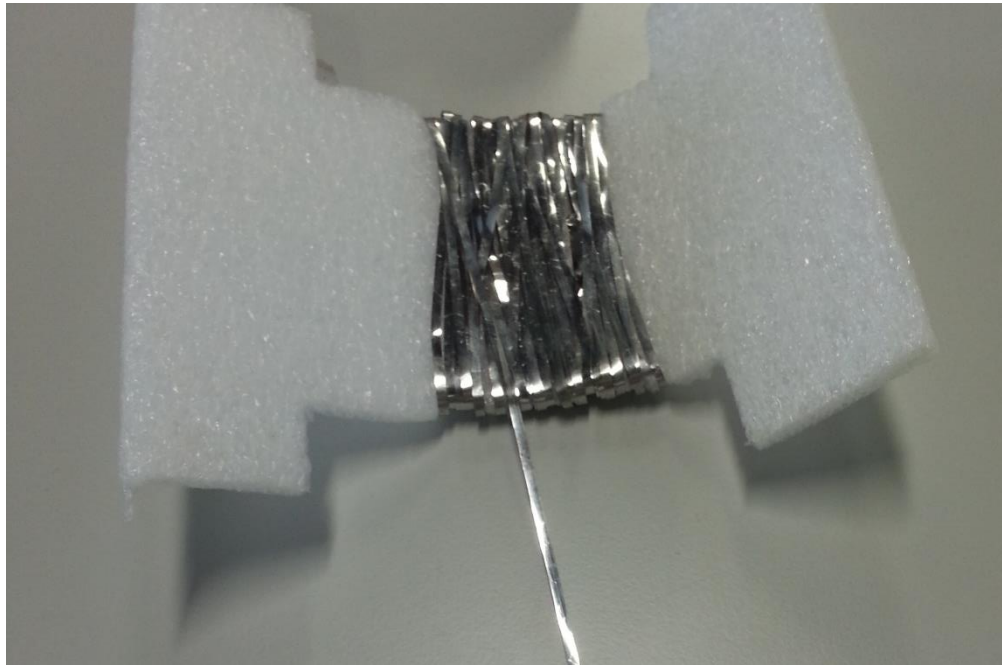


Figure 4.3: Tabbing Wire

The solar modules were first being connected together in a string of nine pieces and then parallel four strings to become a panel. Before connecting in parallel, each string V_{oc} and I_{sc} is checked by multimeter to ensure the connection has good contact and the solar module works. With the specification given for the solar module, we

can calculate the total voltage and current outputs for the solar panel under no shading condition.

Given $V_{mpp} = 2 \text{ V}$ and $I_{mpp} = 60 \text{ mA}$ for one solar module, connecting nine in series and four in parallel, each solar panel will have the output as,

$$\text{Voltage} = 2 \text{ V} \times 9 = 18 \text{ V}$$

$$\text{Current} = 60 \text{ mA} \times 4 = 0.24 \text{ A}$$

$$\text{Power} = 18 \text{ V} \times 0.24 \text{ A} = 4.32 \text{ W}$$

4.2 Data Logger and IV Curve Tracer

The data logger is aim to record the output from the solar panel and thus it must be able to measure the voltage, current and power values accurately and precisely. Others than that, it also serve as an IV tracer. It can be achieved by implementing a potentiometer as the load. By adjusting the resistance from lowest to highest, the voltage output will change from minimum to maximum while the current output change from maximum to minimum. By plotting out each point of the measured data, an IV curve can be found. The greatest advantages of this data logger is that it can collect multiple inputs at the same time, which other commercial IV tracer unable to do so. Thus, the output from three solar panels can be collect and save simultaneously.

4.2.1 Voltage, Current and Power Measurement

Firstly, the Arduino measure the voltage value with its analog pin. As the analog pin of Arduino is restricted to a maximum of 5 V, the voltage has to be scale down before entering Arduino for measurement. In order to do that, voltage divider was used and the circuit is designed in such a way that the output from it will be less than 5 V. From the calculation above, the solar panel have a rated output voltage of 18 V so the voltage divider circuit have to be able to scale down this voltage to less than 5 V.

The voltage divider have 2 resistors with the value of $R_1 = 47 \text{ k}\Omega$ and $R_2 = 10 \text{ k}\Omega$. The values of these two resistors can be change as long as the ratio of it remains the same. Notice that the value of R_1 and R_2 is high although the same ratio can be achieve using other smaller value resistor. This is to eliminate and minimize the power losses as there will be higher current flow when resistance is low. Figure 4.4 shows the voltage divider circuit.

$$V_{out} = \frac{R_2}{R_1 + R_2} \times V_{solar}$$

$$V_{out} = \frac{10 \text{ k}\Omega}{47 \text{ k}\Omega + 10 \text{ k}\Omega} \times 18 \text{ V} = 3.16 \text{ V}$$

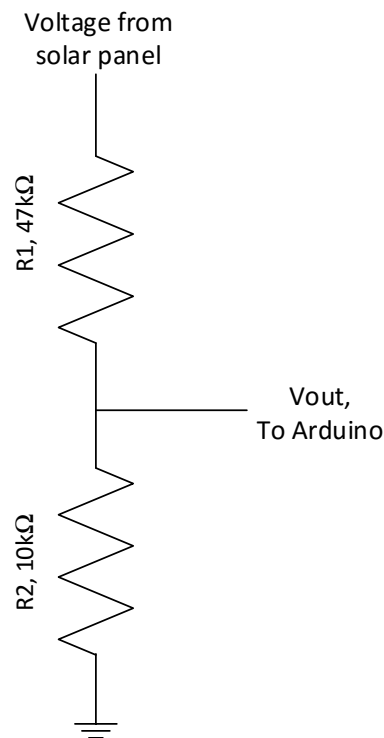


Figure 4.4: Voltage Divider

Arduino have a built in 10 bit ADC that convert the signal from the analog inputs to a corresponding digital values. A 10 bit resolution ADC will have 1024 unique values with respect to 5 V. In other word, each bit is representing 4.88 mV.

Thus, in order to measure the voltage accurately using Arduino, some calculation is needed.

$$V_{out} = A_0 \times \frac{5}{1023}$$

$$Actual\ voltage = V_{out} \times \frac{57\ k\Omega}{10\ k\Omega}$$

Where A_0 is the values read from the Arduino analog pin.

Next, the current measurement is achieved by using an ACS712 Hall Effect current sensor. There are three types of ACS712 current sensor that has different measurement range which are 5 A, 20 A and 30 A. The sensor used in this project is 20 A. From the datasheet, the sensor measure positive and negative 20 A which correspond to its analog output of 100 mV / A. Also from the datasheet, the sensor will have a 2.5 V offset which means that there will be a 2.5 V even no current is flowing through. The calculation for current measurement is as follow,

$$V_{out} = A_1 \times \frac{5}{1023}$$

$$V_{offset} = V_{out} - 2.5$$

$$I = \frac{V_{offset}}{100}$$

After getting voltage and current values, the power can be calculate by multiplying voltage and current. Figure 4.5 shows the current sensing circuit.

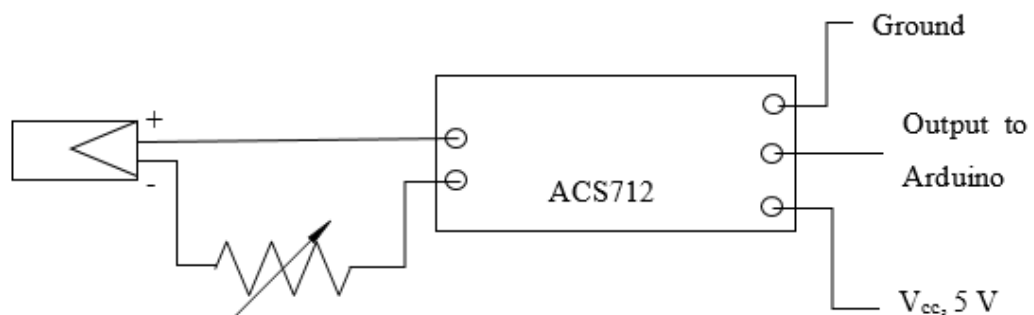


Figure 4.5: Current Sensing Circuit

The complete circuit for the voltage and current measurement is shown as Figure 4.6. Noted that this is not the complete circuit of data logger as this does not include the connection of LCDs and button. Figure 4.7 shows the complete circuit of the data logger.

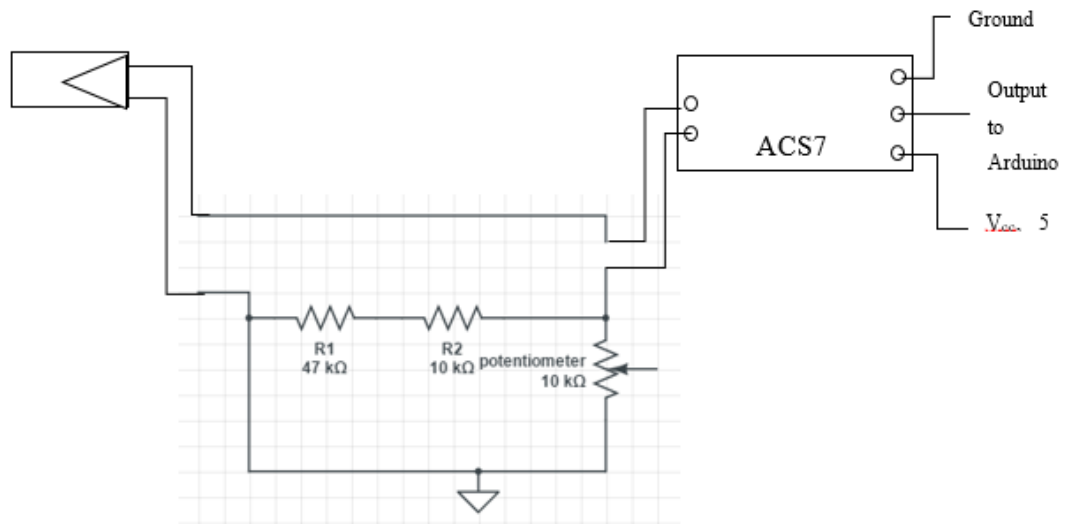


Figure 4.6: Complete Sensing Circuit

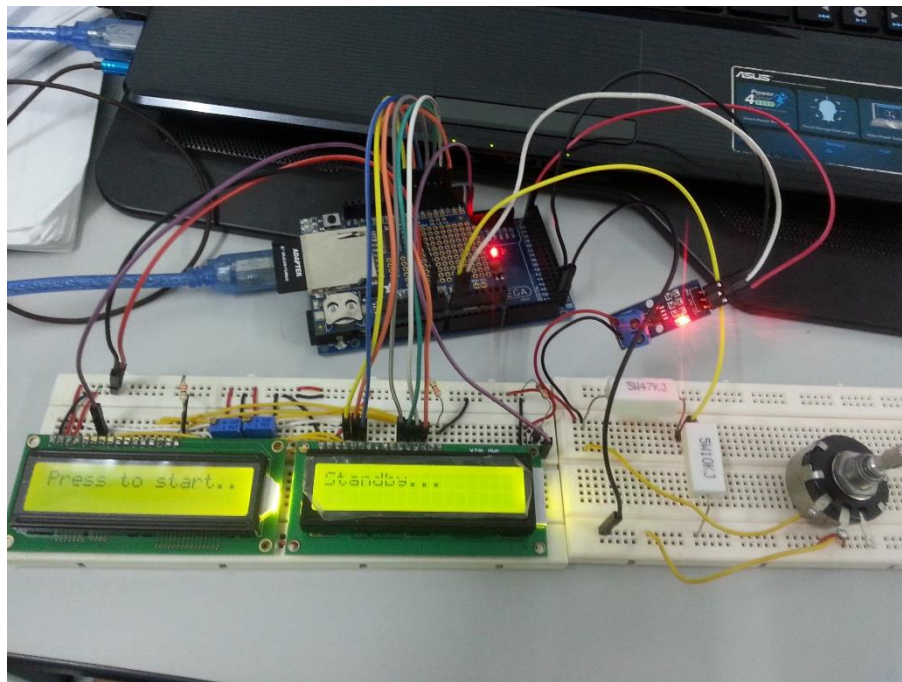


Figure 4.7: Complete Circuit of Data Logger

4.2.2 Additional Features

Others than the expected function that a data logger should achieved which is logging accurate voltage, current and power measurements into an SD card, this data logger also comes with two extra features that worth mentioning. These two features are a start / pause button and LCD display.

Originally, the data logger start logging the data into SD card at the moment it is power on. Moreover, the data logger takes in data continuously with the desire interval time set by the user, it is not possible to pause the data logger half way and continues back from where it stop. In the application of measuring power from solar panel, it is well aware that solar panel takes around 15 minutes to reach thermal equilibrium. This means that the data output from the solar panel for the first 15 minutes might be not consistent and thus not convincing. This button comes in handy at the time like this as the data logger will not start even after the power is turn on unless the button is pressed. Further, the button also allow the user to pause the data logging process at any time and resume it whenever the user want it. For example, when the irradiance is too low for measurement, the user can press the button to pause it and resume it back when the irradiance rise.

The next feature is the display of LCD. Although the data is being log into SD card, it will still be better if there is a display to show the data instantaneously so that the accuracy of the data can be monitor. With Arduino, we can monitor every data output in a computer through a USB interface. However, the data logger is meant for portable use and it will be troublesome to carry a computer around every time in order to read the output instantaneously. With the aim of increasing the portability of the data logger, LCD is added so that the data can be monitor even without a computer. One of the advantages of using this LCD is that it is easy to use and customizable by the user, so the user can display any data he wish. Figure 4.8 shows the different display on the LCD.

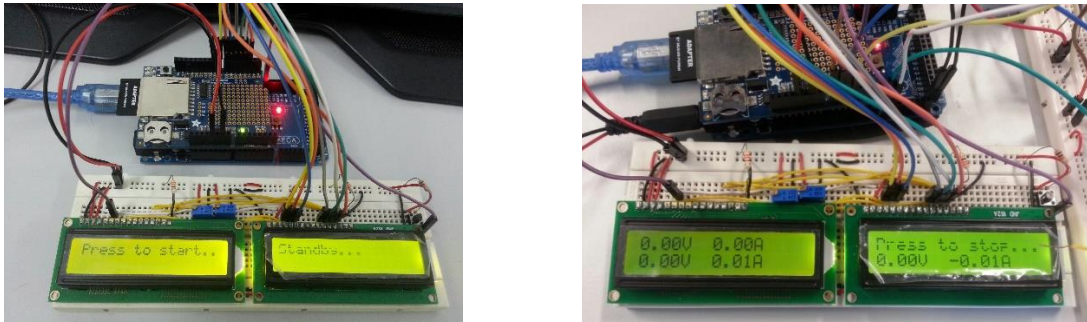


Figure 4.8: LCD Display

4.2.3 Problems Encounter and Solution

Throughout the development process of the data logger, there is some problems encounter. These problems involves in term of both software and hardware. Despite all the difficulties faced, multiple different approaches was tried to solve the problems.

The first problem occurs at the real time clock (RTC), where every time the data logger restart the date and time recorded is not accurate unless otherwise reset it by re-upload it to the Arduino board. After some trouble shooting, it was found that the coin battery which used to power RTC on the data logging shield had fully depleted. The problem is solved by replacing the battery. Following by this, a software problem arise where the data file saved in SD card is overlapping every time. In other words, each time the data logger restart, the newly added data will erase and replace the old data. Forever there will only be one data file exist in the SD card as new data will replace the old data instead of generate a new file and saving in it. After studying on the code, the problem is resolved. A loop is added to check the exiting file in the SD card and write the file name. Every time the power is turn on, the loop check whether a file with same name is exist starting from “LOGGER00” to “LOGGER99”, a new file will be generate if it does not exist and the new data will be logged into it instead of replacing on the old data. Figure 4.9 shows the example of the data saved with the Arduino.

	A	B	C	D	E	F	G	H
1	millis	Time	Voltage(SP)	Current(SP)	Voltage(TCT)	Current(TCT)	Voltage(BL)	Current(BL)
2	12961	3/8/2016 12:45	19.09	-0.39	19.06	-0.22	19.45	-0.23
3	15121	3/8/2016 12:45	19.3	0.01	19.28	0.02	19.67	0.02
4	16984	3/8/2016 12:45	19.31	0	19.28	0.03	19.7	0.03
5	18847	3/8/2016 12:45	19.31	0	19.28	0.03	19.7	0.02
6	20709	3/8/2016 12:45	19.28	0	19.28	0.02	19.7	0.03
7	22573	3/8/2016 12:45	19.28	0	19.28	0.03	19.68	0.03
8	24435	3/8/2016 12:45	19.25	0	19.25	0.02	19.68	0.02
9	26300	3/8/2016 12:45	19.15	0	19.17	0.03	19.59	0.02
10	28169	3/8/2016 12:45	19	-0.01	19.02	0.03	19.46	0.02
11	30032	3/8/2016 12:45	18.77	0	18.8	0.03	19.27	0.03
12	31895	3/8/2016 12:45	18.51	0	18.55	0.03	19.01	0.03
13	33757	3/8/2016 12:45	18.44	0	18.46	0.04	18.86	0.02
14	35619	3/8/2016 12:46	18.64	0.01	18.61	0.04	18.95	0.03
15	37480	3/8/2016 12:46	18.9	-0.01	18.87	0.04	19.2	0.03
16	39343	3/8/2016 12:46	19.13	-0.01	19.1	0.04	19.44	0.03
17	41205	3/8/2016 12:46	19.33	0	19.3	0.04	19.66	0.03
18	43067	3/8/2016 12:46	19.48	0	19.45	0.05	19.83	0.03
19	44939	3/8/2016 12:46	19.59	0	19.57	0.04	19.96	0.03
20	46802	3/8/2016 12:46	19.59	0	19.62	0.04	20.01	0.03
21	48665	3/8/2016 12:46	19.56	0.01	19.59	0.04	20.01	0.03
22	50528	3/8/2016 12:46	19.53	0.01	19.56	0.04	19.99	0.02
23	52389	3/8/2016 12:46	19.53	0.01	19.56	0.04	19.99	0.03

Figure 4.9: Logged Data by Arduino Data Logger

Others than the software problem, the circuit also faced some problem which the measured values is not precise and fluctuated particularly for current. After the circuit was done assembly, the measurement accuracy was tested by supplying a constant 5 V 3 A. It was found that the current measurement was not stable and keep “jumping” around. After some deeper studied on the ACS712 current sensor and troubleshooting, it was able to identify that the cause of this is the unstable input voltage for the current sensor. When the input voltage is not stable, it cause the references voltage and the offset value to oscillate. In the circuit, a single 5 V power supply is used to power two LCDs and three ACS712 currents sensor splitting on 2 different breadboards, which is the main reason of unstable input voltage. The problem is then resolve by supplying the current sensor an independent constant 5 V power supply.

The last problem which is also the most critical problem arise when the IV curve was plotted from the data collected. From the curve, it is obvious that all the collected data are concentrated at the two ends of the graph, there is only less than 3 points at others part of the graph. Noted that the maximum current output for a solar panel is 0.24 A as calculated from section 4.1 and the ACS712 current sensor used is 20 A. From here we can make the assumption that the 20 A current sensor sensitivity is not precise enough for small current variation which is from 0 to 0.24 A. The

assumption is then confirm by monitoring the analog read values from the current sensor through the serial window on a computer. When the potentiometer was adjusted from minimum to maximum, the values of analog read only change 1 bit. Figure 4.10 shows an IV curve plotted from the data collected with Arduino.

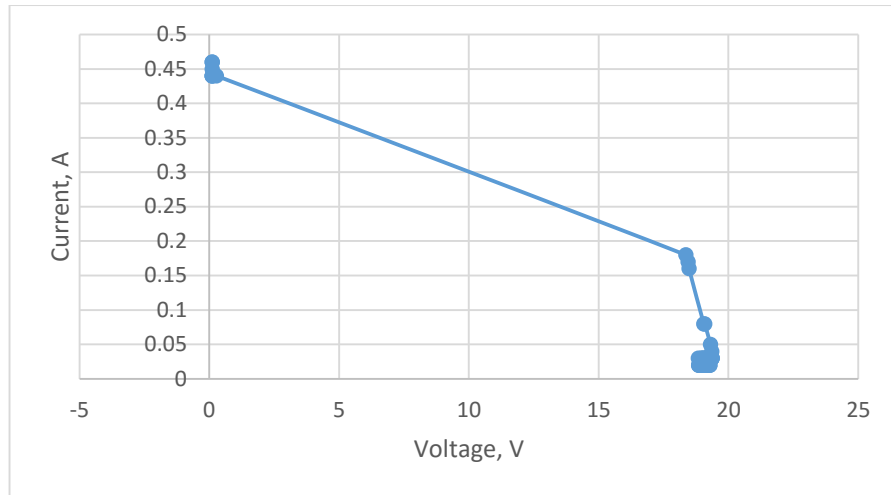


Figure 4.10: IV Curve by Arduino Data Logger

In order to solve this sensitivity problem, several approach has been done. First, a lower rating current sensor, 5 A was used to replace the 20 A, but unfortunately it is still consider big for this 0.24 A maximum current application and do not give any significant improved result. Smaller current sensor such as 1 A should be more suitable but it is not economically available. The second approach here is by using a shunt resistor instead of using current sensor. The current pass through the shunt resistance can be calculate by using Ohm's Law as the resistance value is known and the voltage can be measure by using Arduino. Unfortunately, another problem emerges as the voltage across the shunt resistance is too high for Arduino. If a voltage divider is add in front of the shunt resistance to lower the voltage, the current is consume by the resistance in the voltage divider. In other word, when current measurement is accurate the voltage across it is too high for Arduino, when the voltage is lower down with voltage divider there is no current left to be measure.

As this data logger have the limitation of measuring small current variation precisely, it is then decided to replace the data logger with a more accurate IV tracer

for data collection process, which is PVPM1000CX IV Curve Tracer. For higher current, the data logger is working fine and able to give accurate measurement as was tested in the lab. However, for small current application, some modification and improvement can be done such as using more suitable current sensor values or use a 16 bit ADC instead of the Arduino built in 10 bit ADC.

CHAPTER 5

Results and Discussions

In this chapter, all the data collected is plot in IV curve and PV to study the performance of each of the solar panel under the partial shading condition. Each graph consists of three series of data from three different solar panel so that the differences between them can be see more clearly. However, some of the graphs might only consist one type of solar panel but with different partial shading pattern. The partial shading pattern is as discussed in section 3.4.1.

First of all, it is clear that under no shading condition, three solar panel will have the same total power output with same irradiance condition. Figure 5.1 and Figure 5.2 prove that the theory is correct as all the three solar panels have identical IV curve and PV curve. The V_{oc} is 18.9 V and the I_{sc} is 0.35 A under the irradiance of $920 \text{ W} / \text{m}^2$, the power output is 4.4 W.

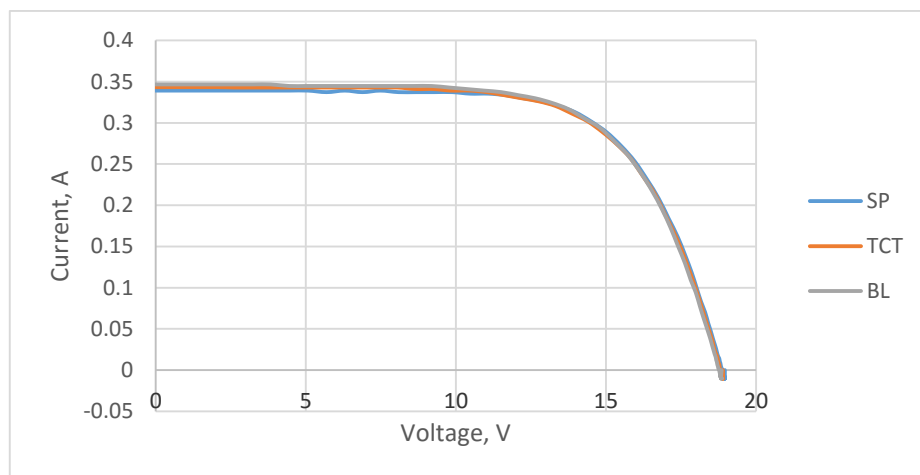


Figure 5.1: IV Curve for No Shading

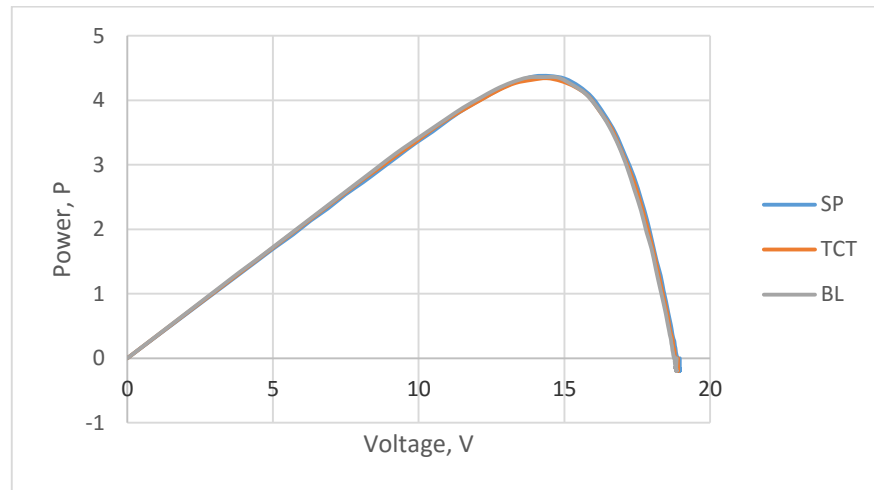


Figure 5.2: PV Curve for No Shading

When there is a whole column being shaded, the I_{sc} drop to 0.26 A but the voltage only slightly decrease and remains almost the same for all three types of solar panels as shown in Figure 5.3. Noted that the TCT have slightly higher I_{sc} compare to the others two, however this is not significant enough to increase total power output. The power output is 3.4 W when a column is being shaded as shown in Figure 5.4.

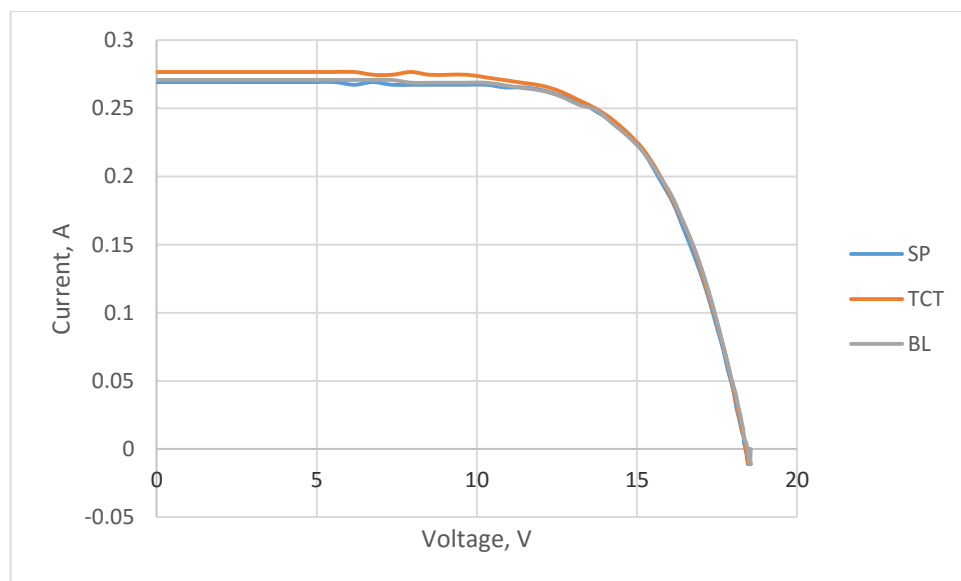


Figure 5.3: IV Curve for 1 Columns Shading

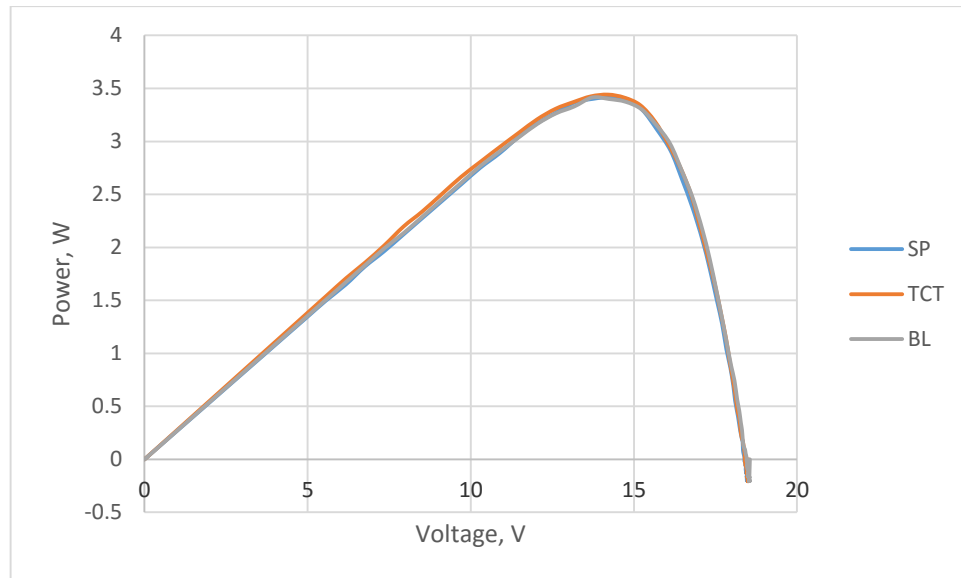


Figure 5.4: PV Curve for 1 Columns Shading

Moving on to 2 column shading, at this time, half of the solar cells was shaded vertically. As current is added up for every string connect in parallel, when two out of four of the string was shaded, the I_{sc} also drop by half to 0.17 A only. The V_{oc} is now 18 V, compare to non-shaded 18.9 V, it is still consider high as total voltage output is the sum from series connection. Thus, shading the whole column will not affect the voltage output very much. The power output at this shading condition is 2.2 W. Figure 5.5 and Figure 5.6 shows the IV curve and PV curve respectively.

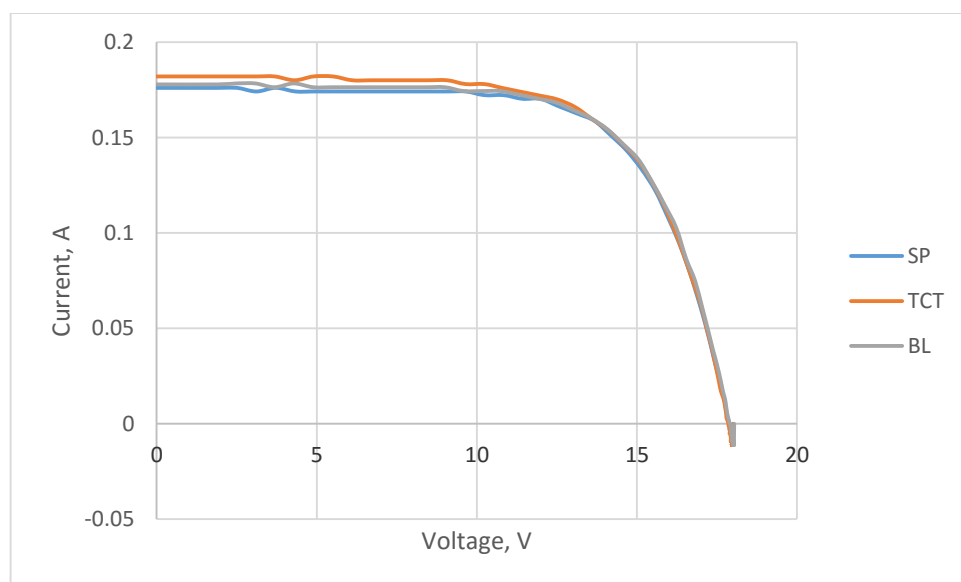


Figure 5.5: IV Curve for 2 Columns Shading

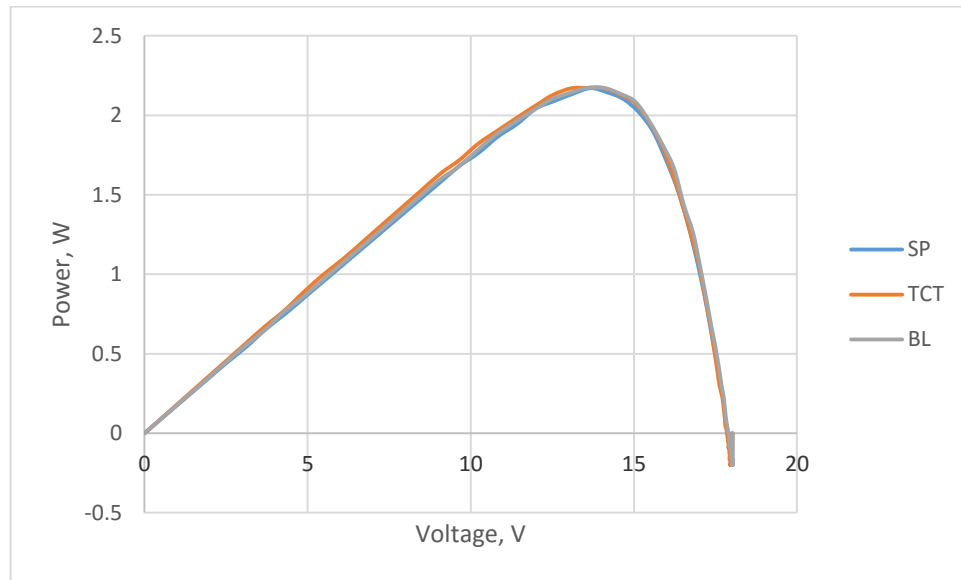


Figure 5.6: PV Curve for 2 Columns Shading

When three columns was shaded out of four columns, there is some interesting finding shows. From Figure 5.7 and Figure 5.8, SP have higher power output with higher V_{oc} and I_{sc} compare to TCT and BL. The power output for SP is 2.1 W which is higher a lot higher than 0.9 W from TCT and BL

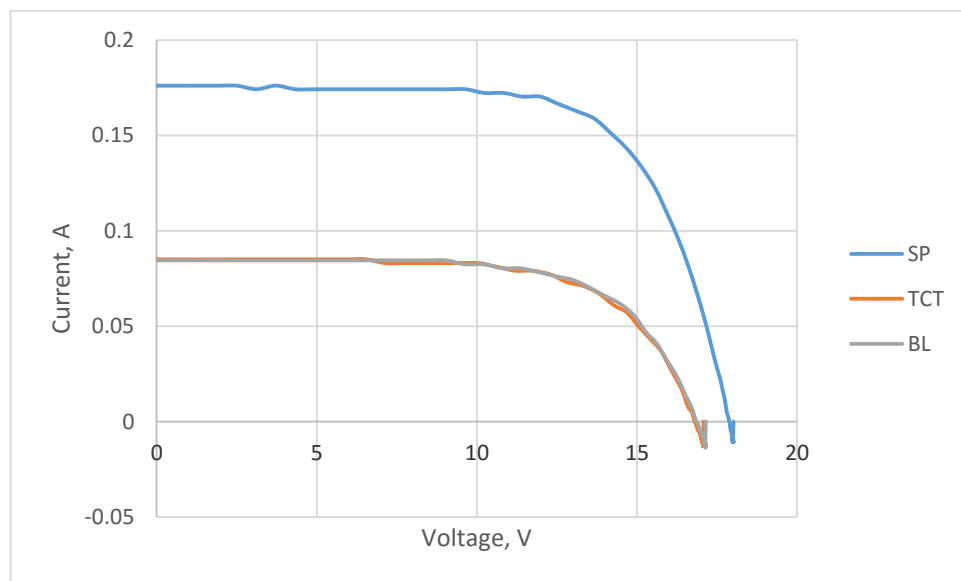


Figure 5.7: IV Curve for 3 Columns Shading

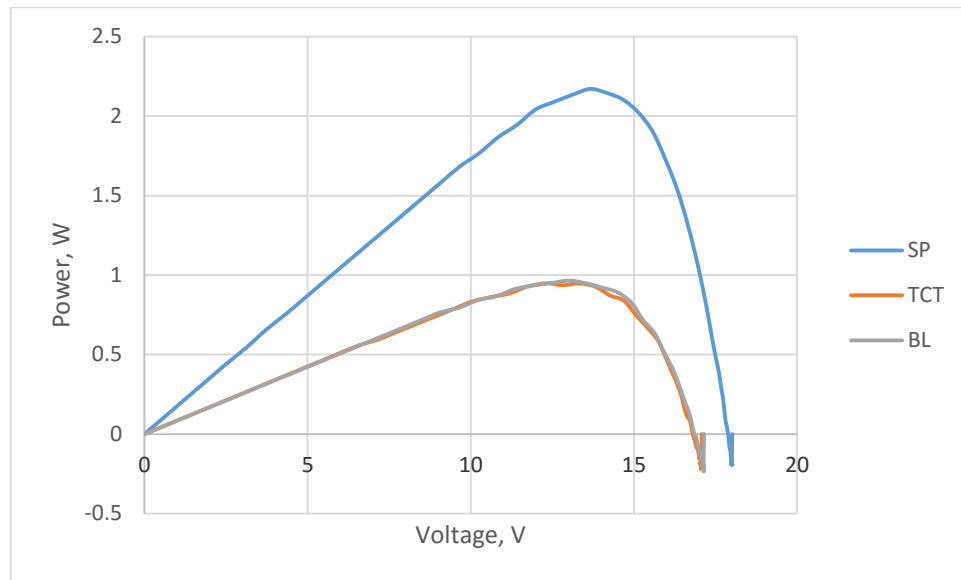


Figure 5.8: PV Curve for 3 Columns Shading

Summing up the points, as more columns are being shaded, the power drop more with the lower current output. However, for SP connection, the power output did not further decrease even when the shading extend from two columns to three columns, the power remains the same. Table 5.1 give a better illustration on the power output for all three solar panels with the increasing of shading area. Figure 5.9 and Figure 5.10 shows the IV and PV curve respectively for TCT column shading.

Table 5.1: Power Output for Column Shading

Power, W Shading	SP	TCT	BL
No shading	4.4	4.4	4.4
1 column	3.4	3.4	3.4
2 columns	2.1	2.1	2.1
3 columns	2.1	0.9	0.9

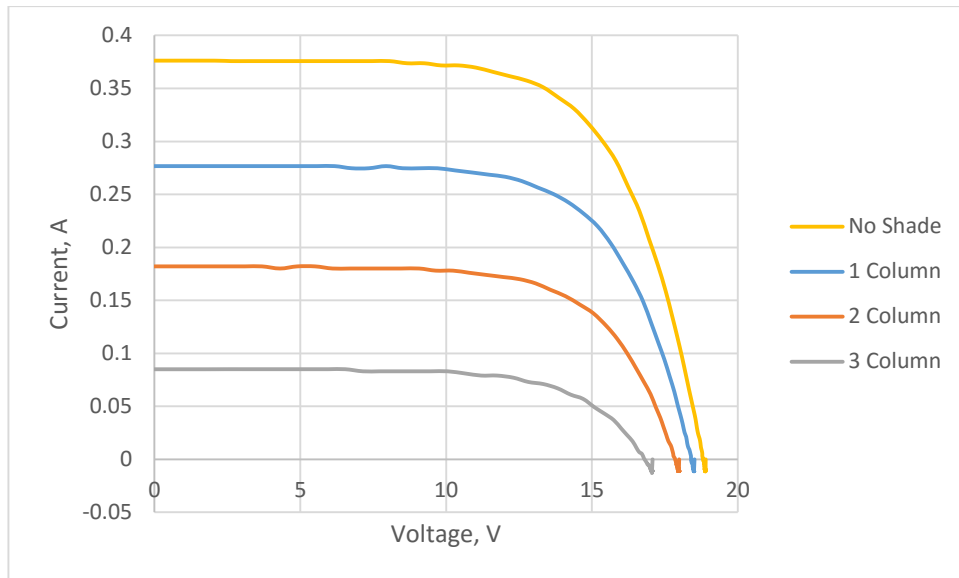


Figure 5.9: IV Curve for TCT Columns Shading

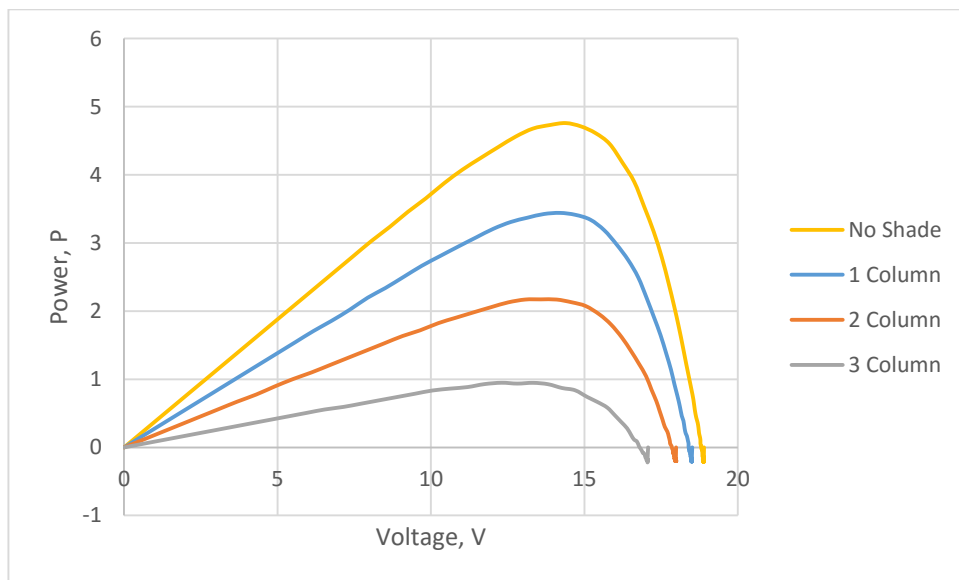


Figure 5.10: PV Curve for TCT Columns Shading

After the shading in column was analysed, the analysis move on to the shading for row. From the experiment, the results shows in Figure 5.11 and 5.12 justify that when a whole row of the solar panel was shade, there is no power output at all. There are total of nine rows in the solar panel, there will be no power output regardless of which row is being shaded. Every solar cells in a string will have the same current flowing through and this current sums up when connect parallel with another string.

When a whole row is being shaded, one solar cell from each strings will have very high resistance and thus blocking the current flow in each of their particular string. As a result of that, there will be no power output if any of the row is being shaded.

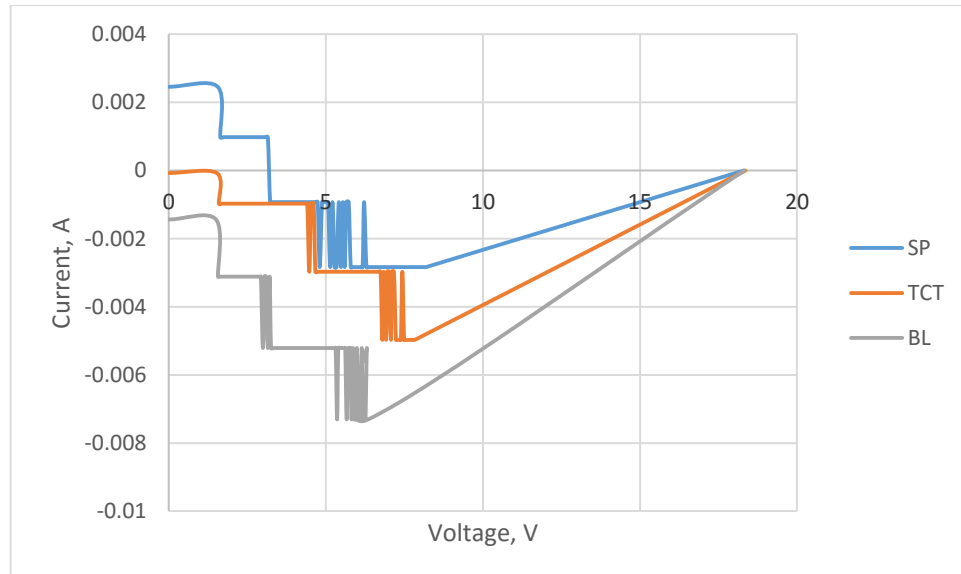


Figure 5.11: IV Curve for 1 Row Shading

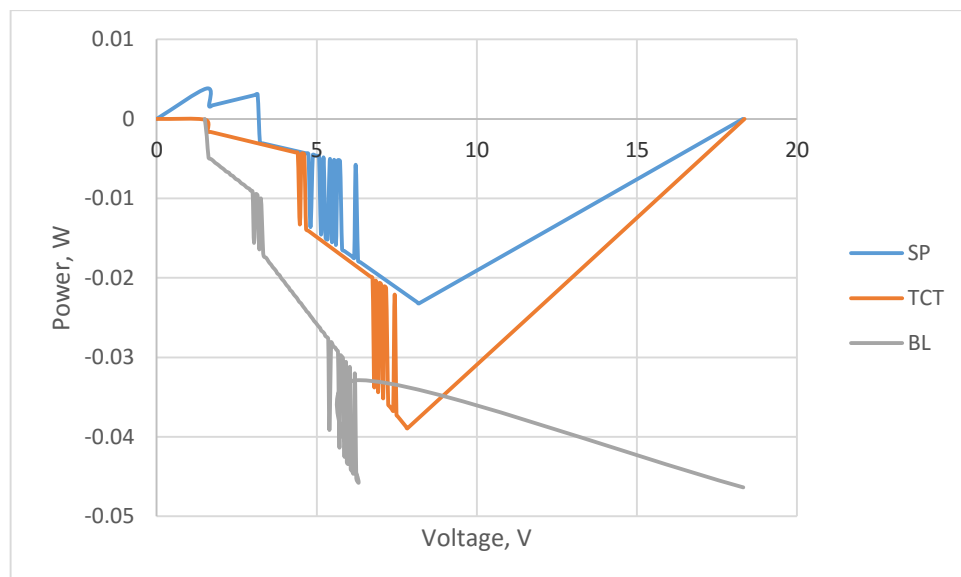


Figure 5.12: PV Curve for 1 Row Shading

From the result, we know that when a whole column are being shaded, all three types of solar panel will have the same power output reduction. Only when three

columns are shaded, TCT and BL have same power output but SP have higher. What if only a few cells in a column was shaded instead of the whole column? From Figure 5.13 and 5.14, it is obvious that TCT will have the highest power output follow by BL and lastly is SP. Noted that all three solar panels have same V_{oc} but different I_{sc} which cause the difference power output. By increasing the number of cells shaded in a column, the power output is lower and the output difference between each type of solar panel is larger.

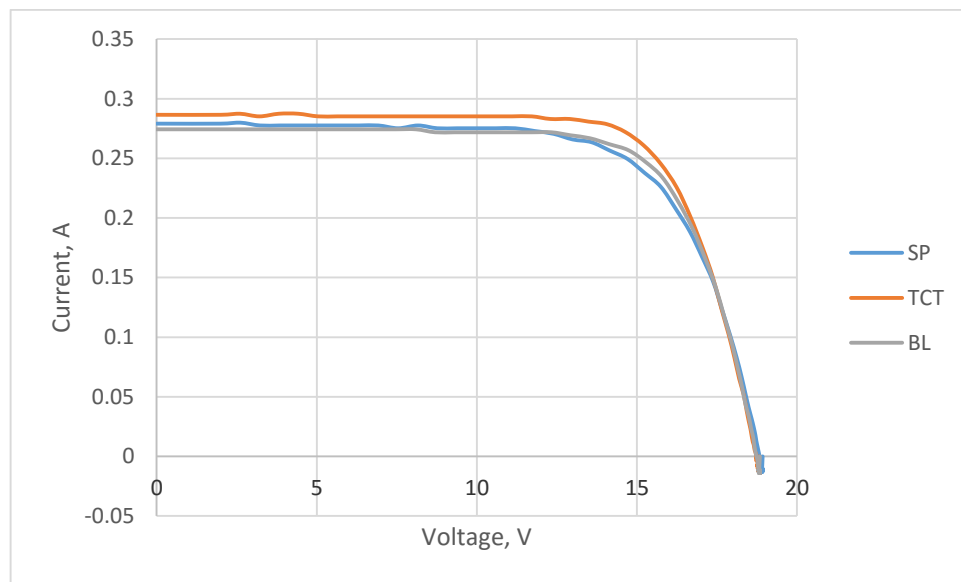


Figure 5.13: IV Curve for 4 Cells in a Column Shading

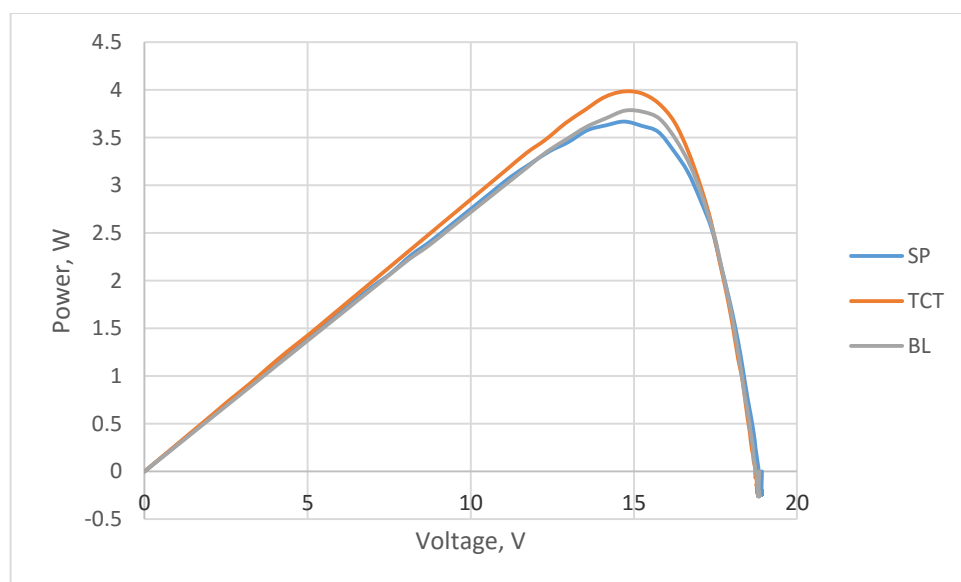


Figure 5.14: PV Curve for 4 Cells in a Column Shading

Next, the shading condition is that two cells in a row being shaded. When whole row is being shaded, there will be no power output as there is no current flow, but when only half row is being shaded, the I_{sc} is 0.185 A which is almost half the I_{sc} when there is no shading, shown in Figure 5.15. Looking at the PV curve from Figure 5.16, TCT have the highest power output which is 3.05 W, BL have slightly lower which is 2.8 W and SP have lowest of 2.3 W. From study, we know that the power output will drop by half as two out of four cells in a row was being shaded. The SP PV curve prove this as its power output is half of the power when there is no shading, 4.4 W. With TCT and BL connection, the power output can be increase by 32% and 21% respectively.

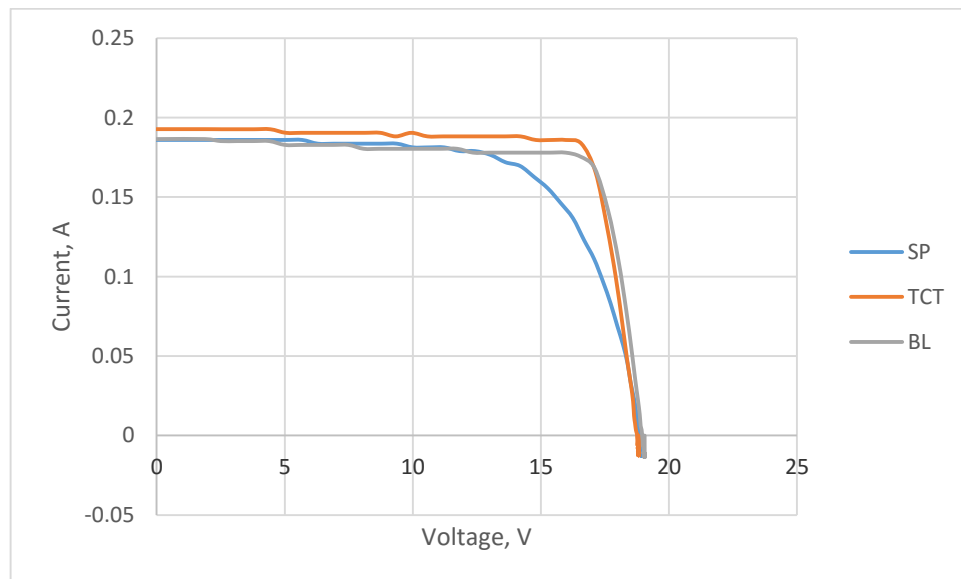


Figure 5.15: IV Curve for 2 Cells in a Row Shading

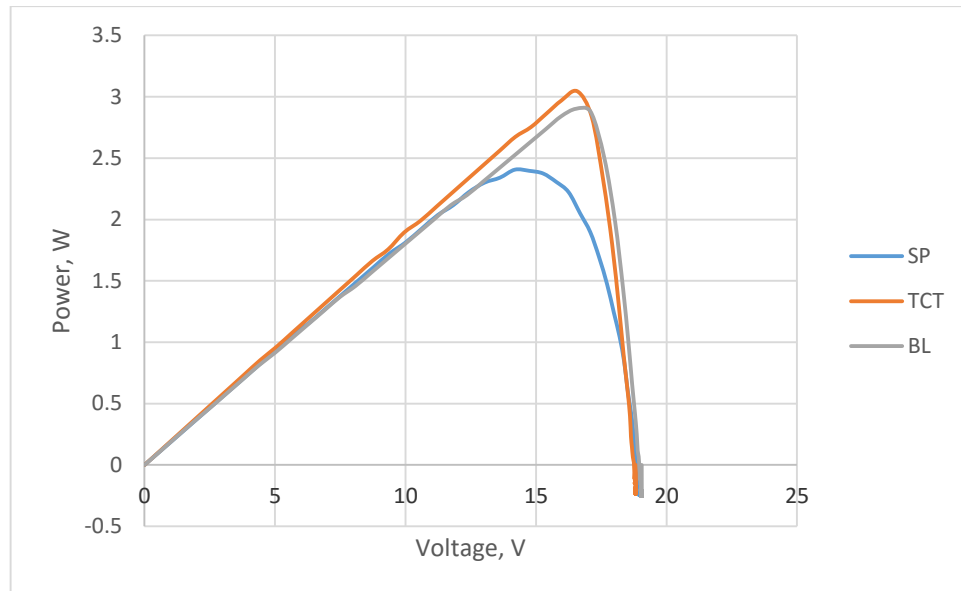


Figure 5.16: PV Curve for 2 Cells in a Row Shading

For two cells shaded in the centre, the IV curve and PV curve shows in Figure 5.17 and 5.18 have very similar graph as in Figure 5.15 and 5.16, when two cells in a row was shaded. This is because the shading condition is actually also two cells shaded in a row but only shift of position.

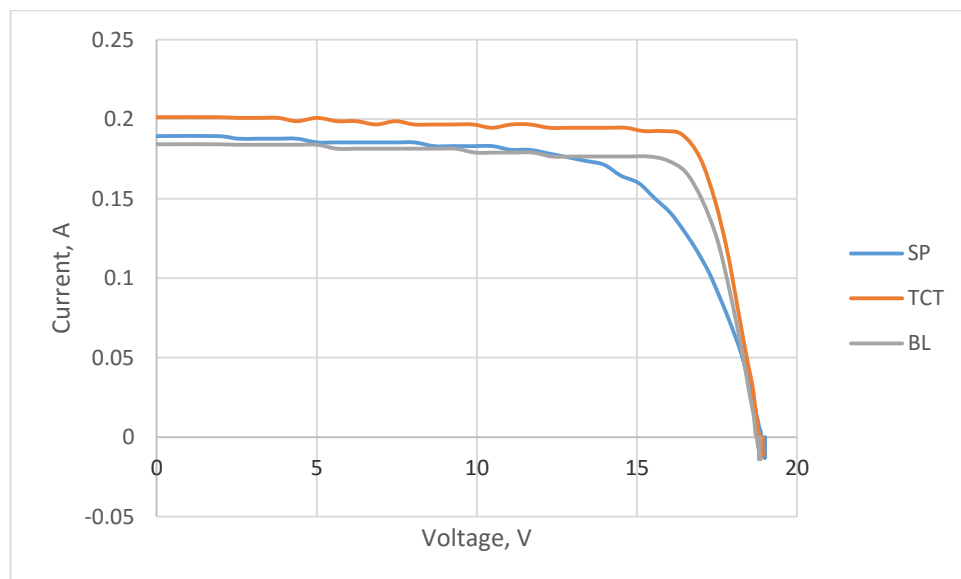


Figure 5.17: IV Curve for 2 Cells in Centre Shading

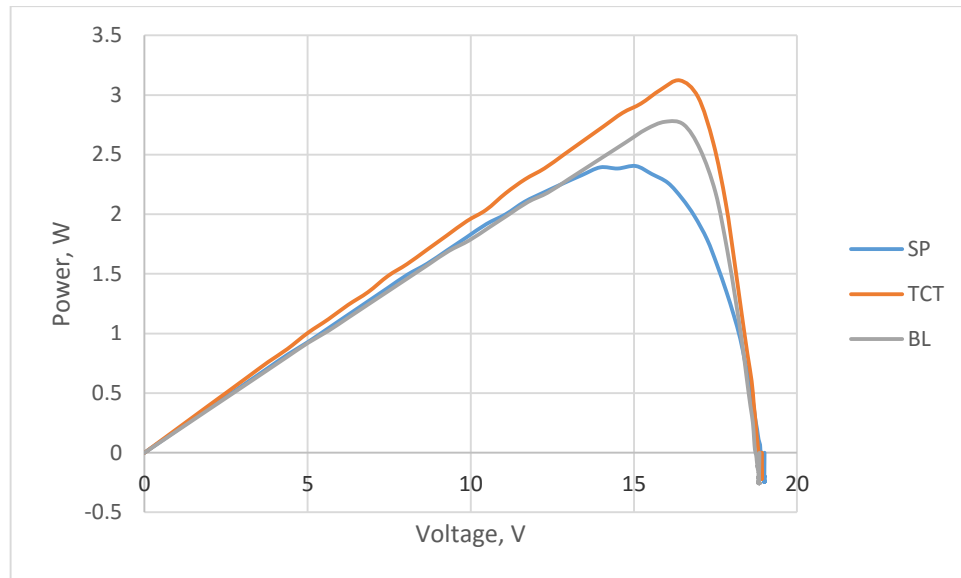


Figure 5.18: PV Curve for 2 Cells in Centre Shading

For eight cells shaded in centre, Figure 5.20 shows the power output for TCT is 2.72 W, BL is 2.6 W and SP is 2.4 W. Figure 5.19 shows the IV curve. Generally, TCT connection give highest power output under partial shading condition follow by BL and SP. However, there is still some situation where TCT might not be the highest as we can see from Figure 5.7 and figure 5.8. The reason that TCT have high power output at most of the partial shading condition is that its interconnection between the solar cells provide more pathway for the current to flow and bypass the shaded solar cell.

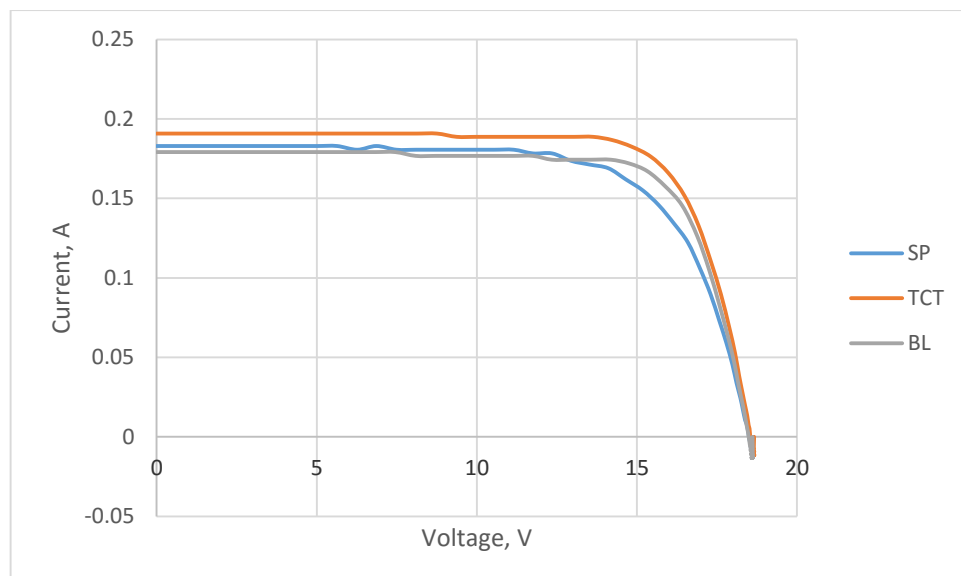
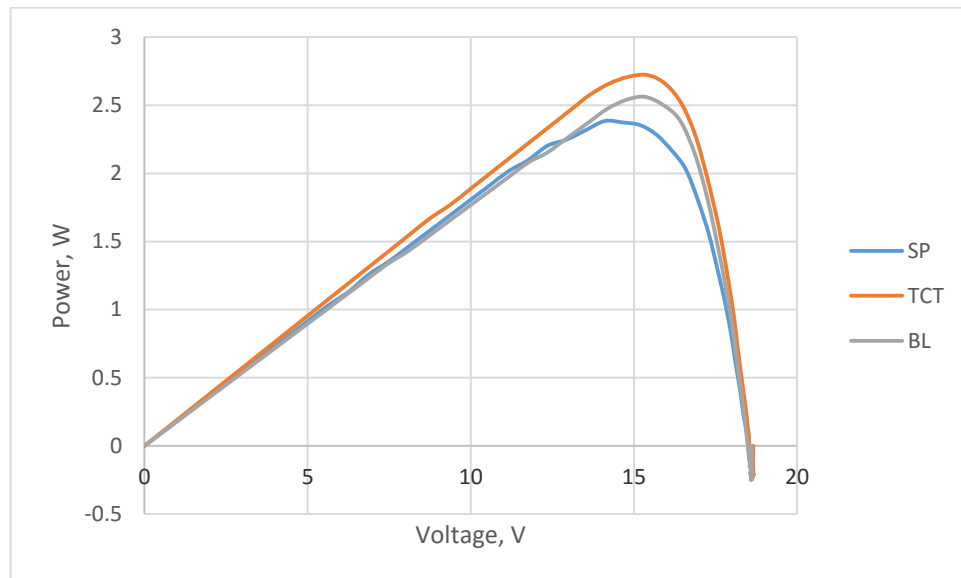


Figure 5.19: IV Curve for 8 Cells in Centre Shading**Figure 5.20: PV Curve for 8 Cells in Centre Shading**

CHAPTER 6

CONCLUSION

6.1 Conclusion

In conclusion, all three project objectives have been met successfully at the end of the project. From this project, the author was able learnt on various interconnection schemes other than the commonly found Series Parallel (SP). These includes Total Cross Tied (TCT), Bridge Link (BL), Honey Comb (HC) and etc.

Others than that, the author was able to construct three 4×9 solar panels with the interconnection of SP, TCT and BL. This is achieved by connecting small solar module with tabbing wire. Further, the effects of partial shading on different interconnection solar panels were studied by monitoring the IV curve and PV curve. It can be concluded that TCT and BL will have higher power output than the conventional SP under partial shading condition. Among all the interconnection schemes, TCT connection show the best performance under partial shading condition as it has more current pathway for unshaded solar cell.

Besides meeting all the objectives, the author also achieved something as extra and gain benefits from it. In this project, a simple IV tracer with the ability of logging data was develop. Through the development of this IV tracer, the techniques to measure voltage and current accurately by using Arduino was learnt. On top of that, author was able to learnt how to logged data into an SD card and most importantly, programming language was enhanced. This IV tracer and data logger is important to

this project as it has the advantage to collect multiple outputs from the solar panels simultaneously, which cannot be done by others commercial IV tracer.

6.2 Future Implementation

6.2.1 Shading Patterns and Data Collection

From this project, I have learnt that different shading patterns give rise to different performance on each solar panels. Thus, more shading patterns can be model and simulate on the solar panel in order to have deeper understanding on how different interconnection can increase the power output. Some suggested shading patterns are shade diagonally, more solar cells shade in random and non-uniformly, shade half of the solar cell and etc.

Throughout the project, it is clear that the even a small variation in solar irradiance will affect the power output significantly. In this project, the data collection is only done under the irradiance between $850 \text{ W} / \text{m}^2$ to $950 \text{ W} / \text{m}^2$. It is suggested that more data can be collect under lower irradiance such as $600 \text{ W} / \text{m}^2$ or $200 \text{ W} / \text{m}^2$. By doing so, someone can study and understand better at what irradiance level the interconnection scheme will have the greatest effect and give most significant increment at the total power output.

6.2.2 IV Tracer

Despite the IV tracer was able to measure voltage and current accurately and logged it into an SD card, it has a limitation which is unable to detect a small changes of current. For the IV tracer to have a better performance and trace the IV curve more accurately, it must be able to detect the smallest current variation. In order to do that, smaller range of current sensor can be used. Others than that, an ADC with higher bit resolution can

be used instead of using the built in ADC in Arduino which is only 10 bit. For example, the Adafruit ADS1115 16 bit ADC.

REFERENCES

- Berning, K., 2011. *Design of stand-alone renewable power supply systems on Futuna Island, Vanuatu*. Sweden: Uppsala University.
- Bulanyi, P. and Zhang, R., 2014. Shading analysis & improvement for distributed residential grid-connected photovoltaics system.
- Conserve Energy Future, 2015. *Solar Energy*. [online] Available at: <<http://www.conserve-energy-future.com/SolarEnergy.php>> [Accessed 11 July 2015]
- Deshkar, S.N., Dhale, S.B., Mukherjee, J.S., Babu, T.S. and Rajasekar, N., 2015. Solar PV array reconfiguration under partial shading conditions for maximum power extraction using genetic algorithm. *Renewable and Sustainable Energy Reviews*, 43, pp 102 – 110.
- Guo, S., Walsh, T.M., Aberle, A.G. and Peter, M., 2012. Analysing partial shading of PV modules by circuit modelling. *38th IEEE Photovoltaic Specialists Conference (PVSC)*. Austin, TX, 3-8 June 2012.
- János, T. and Elza, K., 2008. Designing and operating passive solar systems. *Environmental Technology*.
- Kaushika, N.D. and Gautam, N.K., 2003. Energy Yield Simulations of Interconnected Solar PV Arrays. *IEEE Transaction on Energy Conversion*, 18 (1), pp 127 – 134.
- Mutoh, N., Ohno, M. and Inoue, T., 2006. A method for MPPT control while searching for parameters corresponding to weather conditions for PV generation systems. *Industrial Electronics*, 53 (4), pp. 1055 – 1065.
- Pachpande, S.G. and Zope, P.H., 2012. Studying the effect of shading on Solar Panel using MATLAB. *International Journal of Science and Applied Information Technology*, 1 (2).
- Petrone, G. and Paja, C.A.R., 2011. Modeling of photovoltaic fields in mismatched conditions for energy yield evaluations. *Electric Power System Research*, 81 (4), pp 1003 – 1013.

- Picault, D., Raison, B., Bacha, S., Casa, J.D.L. and Aguilera, J., 2010. Forecasting photovoltaic array power production subject to mismatch losses. *Solar Energy*, 84 (7), pp 1301 – 1309.
- Rani, B.I., Ilango, G.S. and Nagamani, C., 2013. Enhanced power generation from PV array under partial shading condition by shade dispersion using Su Do Ku configuration. *Sustainable Energy*, 4 (3), pp 594 – 601.
- Shukla, A., 2010. *Optimization for generation scheduling with renewable energy system*. Degree. Thapar University.
- Wang, Y.J. and Hsu, P.C., 2011. An investigation on partial shading of PV modules with different connection configurations of PV cells. *Energy*, 36 (5), pp 3069 – 3078.

APPENDICES

APPENDIX A: Coding

```

#include <LiquidCrystal.h>
#include <SPI.h>
#include <SD.h>
#include <Wire.h>
#include "RTCLib.h"

LiquidCrystal lcd1(8, 7, 9, 5, 4, 3, 2); //define pin for LCD 1
LiquidCrystal lcd2(8, 7, 6, 5, 4, 3, 2); //define pin for LCD 2
RTC_DS1307 RTC; //define the Real Time Clock object
File dataFile; //define data logging file

const int chipSelect = 10; //chip select 10 for Data Shield on Mega
byte logMode = 0; //to check logMode
const int button = 14;
float vsample1 = 0; // for voltage
float asample1 = 0; // for current
float vsample2 = 0;
float asample2 = 0;
float vsample3 = 0;
float asample3 = 0;
float voltage1 = 0.0;
float voltage2 = 0.0;
float voltage3 = 0.0;
float val1; // current callibration
float actualval1; // read the actual current from ACS 712
float amps1 = 0.0;
float val2;
float actualval2;
float amps2 = 0.0;
float val3;
float actualval3;
float amps3 = 0.0;
float watt1 = 0.0;
float watt2 = 0.0;
float watt3 = 0.0;

void setup() {
  Serial.begin(9600);
  lcd1.begin(16, 2);
  lcd2.begin(16, 2);

```

```

pinMode(button, INPUT);           //button as input at pin 14

lcd1.print("Welcome!");
delay(1500);
lcd1.clear();

lcd2.print("Standby...");

Serial.print("Initializing SD card...");
lcd1.print("Initializing ");
lcd1.setCursor(0, 1);
lcd1.print("SD card...");
delay(1500);
lcd1.clear();

pinMode(53, OUTPUT); //set 53 as output for MEGA

//check if the card is present and initialized
while (!SD.begin(10, 11, 12, 13)) {
  Serial.println("Card not insert or failed!");
  lcd1.print("Card not insert");
  lcd1.setCursor(0, 1);
  lcd1.print("or failed!");
  delay(1500);
  lcd1.clear();
}
Serial.println("Card initialized!");
lcd1.print("Card ");
lcd1.setCursor(0, 1);
lcd1.print("initialized!");
delay(1500);
lcd1.clear();

//open file to log data
Serial.println("Opening file...");
lcd1.print("Opening File...");
delay(1500);
lcd1.clear();

char filename[] = "LOGGER00.CSV";
for (uint8_t i = 0; i < 100; i++) {
  filename[6] = i / 10 + '0';
  filename[7] = i % 10 + '0';
  if (!SD.exists(filename)) {
    //only open a new file if it doesn't exist
    dataFile = SD.open(filename, FILE_WRITE);
    break; //leave the loop.
  }
}

if (!dataFile) {
  Serial.println("Error opening file!");
  lcd1.print("Error opening ");
  lcd1.setCursor(0, 1);
  lcd1.print("file!");
  delay(1500);
  while (1);
}
else {
  Serial.println("Logging to:");

```

```

    Serial.println(filename);
    lcd1.print("Logging to:");
    lcd1.setCursor(0, 1);
    lcd1.print(filename);
    delay(1500);
    lcd1.clear();
}

//kickstart the Real Time Clock
Wire.begin();
RTC.begin();

//print the header

dataFile.println("millis,Time,Voltage(SP),Current(SP),Power(SP),Voltage(TCT),Current(TCT),Power
(TCT),Voltage(BL),Current(BL),Power(BL)");
}

void loop() {

    if (digitalRead(button) == HIGH) {
        logMode = 1;           //button pressed
    }
    else {
        logMode = 0;           //button not pressed
    }
    if (logMode == 0) {
        lcd1.print("Press to start...");
        lcd2.print("Standby...");
        delay(100);
        lcd1.clear();
        lcd2.clear();
    }
    else
        datalog();             //if pressed, go to datalog
}

void datalog() {

    logMode = 1;

    do {

        long millisec = millis(); // calculate time in milisec
        long time = millisec / 1000; // convert time to sec

        for (int i = 0; i < 100; i++) {
            vsample1 += analogRead(A0); //read the voltage from the sensor
            asample1 += analogRead(A1); //read the current from sensor
            vsample2 += analogRead(A2);
            asample2 += analogRead(A3);
            vsample3 += analogRead(A8);
            asample3 += analogRead(A9);
            delay(1);
        }
        vsample1 = vsample1 / 100;
        asample1 = asample1 / 100;
        vsample2 = vsample2 / 100;
        asample2 = asample2 / 100;
        vsample3 = vsample3 / 100;
    }
}

```

```

asample3 = asample3 / 100;

//voltage calculation
voltage1 = (((vsample1 * 5.03) / 1023) * 5.7);
voltage2 = (((vsample2 * 5.03) / 1023) * 5.7);
voltage3 = (((vsample3 * 5.03) / 1023) * 5.7);
//callibration, 3.25v is eqv 696 in A2 reading, multiply 2 to get actual voltage

//current calculation
Serial.println(asample1);
val1 = (asample1 / 1023) * 5000;
actualval1 = val1 - 2500; // offset voltage is 2.5v
amps1 = actualval1 / 100; // 100mv/A from data sheet

Serial.println(asample2);
val2 = (asample2 / 1023.0) * 4990;
actualval2 = val2 - 2500;
amps2 = actualval2 / 100;

Serial.println(asample3);
val3 = (asample3 / 1023.0) * 5030;
actualval3 = val3 - 2520;
amps3 = actualval3 / 100;

watt1 = voltage1 * amps1; // power=voltage*current
watt2 = voltage2 * amps2;
watt3 = voltage3 * amps3;

//DATA LOGGING
DateTime now;
dataFile.print(millisecond);
dataFile.print(",");
Serial.print(millisecond);
Serial.print(",");

// fetch the time
now = RTC.now();
// log time
dataFile.print(now.year(), DEC);
dataFile.print("/");
dataFile.print(now.month(), DEC);
dataFile.print("/");
dataFile.print(now.day(), DEC);
dataFile.print(" ");
dataFile.print(now.hour(), DEC);
dataFile.print(":");
dataFile.print(now.minute(), DEC);
dataFile.print(":");
dataFile.print(now.second(), DEC);
dataFile.print(",");

Serial.print(now.year(), DEC);
Serial.print("/");
Serial.print(now.month(), DEC);
Serial.print("/");
Serial.print(now.day(), DEC);
Serial.print(" ");
Serial.print(now.hour(), DEC);
Serial.print(":");
Serial.print(now.minute(), DEC);

```



```

Serial.print(":");
Serial.print(now.second(), DEC);
Serial.println("");

//log sensor values
dataFile.print(voltage1);
dataFile.print(",");
dataFile.print(amps1);
dataFile.print(",");
dataFile.print(watt1);
dataFile.print(",");
dataFile.print(voltage2);
dataFile.print(",");
dataFile.print(amps2);
dataFile.print(",");
dataFile.print(watt2);
dataFile.print(",");
dataFile.print(voltage3);
dataFile.print(",");
dataFile.print(amps3);
dataFile.print(",");
dataFile.print(watt3);
dataFile.println("");

//DISPLAY IN SERIAL MONITOR
Serial.print("VOLTAGE(SP) : ");
Serial.print(voltage1);
Serial.println(" Volt");
Serial.print("CURRENT(SP) :");
Serial.print(amps1);
Serial.println(" Amps");
Serial.print("VOLTAGE(TCT) : ");
Serial.print(voltage2);
Serial.println(" Volt");
Serial.print("CURRENT(TCT) :");
Serial.print(amps2);
Serial.println(" Amps");
Serial.print("VOLTAGE(BL) : ");
Serial.print(voltage3);
Serial.println(" Volt");
Serial.print("CURRENT(BL) :");
Serial.print(amps3);
Serial.println(" Amps");
//Serial.print("POWER :");
//Serial.print(watt);
//Serial.println("Watt");
//Serial.print("ENERGY CONSUMED :");
//Serial.print(energy);
//Serial.println("Watt-Hour");
Serial.println(""); // print the next sets of parameter after a blank line

//DISPLAY IN LCD
lcd1.setCursor(0, 0); // set the cursor at 1st col and 1st row
lcd1.print(voltage1);
lcd1.print("V ");
lcd1.print(amps1);
lcd1.print("A ");
lcd1.setCursor(0, 1);
lcd1.print(voltage2);
lcd1.print("V ");

```

```
lcd1.print(amps2);  
lcd1.print("A ");  
  
lcd2.setCursor(0, 0);  
lcd2.print("Press to stop...");  
lcd2.setCursor(0, 1); // set the cursor at 1st col and 2nd row  
lcd2.print(voltage3);  
lcd2.print("V ");  
lcd2.print(amps3);  
lcd2.print("A ");  
  
dataFile.flush();  
delay(1000);  
  
if (digitalRead(button) == HIGH) {  
    logMode = 0;  
    delay(500);  
}  
else {  
    logMode = 1;  
    delay(500);  
}  
} while (logMode == 1);  
}
```