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Characterisation of a Photovoltaic Module

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Abstract

Most of energy production depends on fossil fuels, which have enormous effects on environment such as pollution, health problems and increasing the risk of global warming. Therefore, the interest in renewable energy source, such as wind and solar, has been renewed. After years of research, the photovoltaic effect has been discovered. Photovoltaic (PV) is device based on semiconductor materials that converts sunlight to electricity. This experiment is about testing a PV module under different condition, at darkness, with different illumination and with external load. Moreover, the report will cover the I-V characteristics and the important parameter of a PV module.

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1. Introduction

Nowadays the electric energy is mostly obtained from fossil fuels. Due to their harmful effects on the environment, they become less attractive sources for generate energy. Recently, many agreements and commitments for reducing carbon emission have been renewed interests in renewable energy source RES such as wind, solar and ocean wave. These sources are sustainable and generate clean energy. One of the most important renewable sources is solar energy. It has been attracting the attention of many engineers, scientists and researchers. Every day the earth received a huge amount of energy from the sun. Sunlight energy can be collated and converted into electricity form using the photovoltaic PV system (Anani, 2013).

Photovoltaic is the simplest technology to design and install. It is also considered to be one of the most expensive renewable technologies. However, it is non-pollutant, environmentally friendly and low maintenance energy source (Chaar et. al., 2011). This laboratory is about testing the performance of a PV panel in different situation at darkness, with different illumination n and with external load, as well as determining the I-V characteristics and obtaining other important parameter for PV module such as fill factor and efficiency.

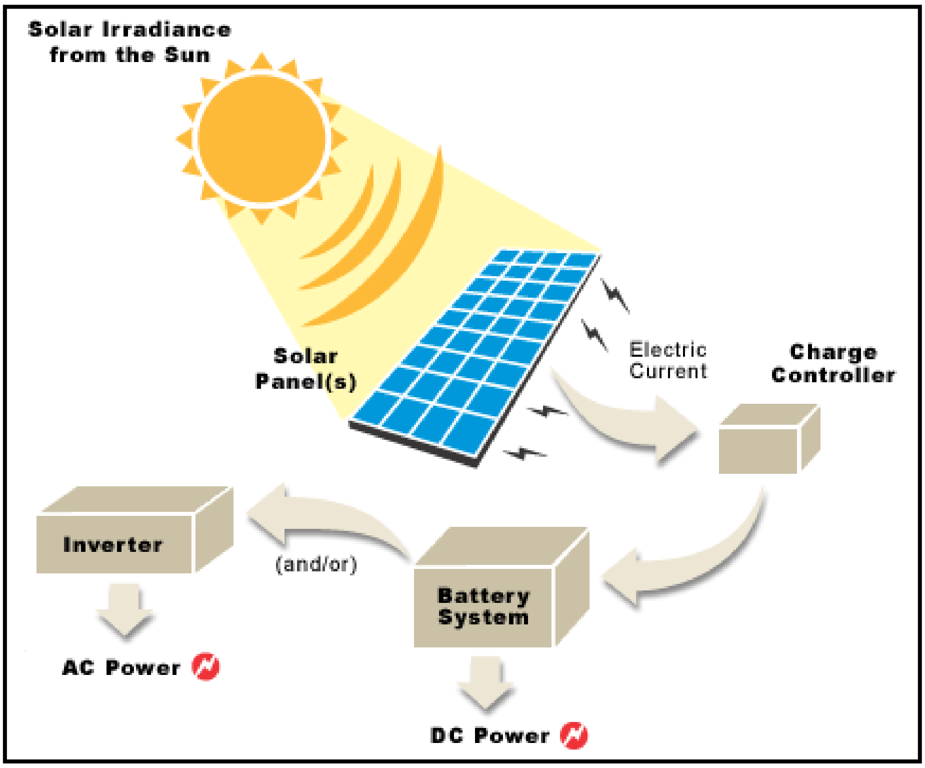

Figure-1: Convert solar irradiance into electricity using PV panel.

2. Aim

- The aim of this experiment is to measure the characteristics of a PV panel.

3. Objectives

- Measure the short circuit current and open circuit voltage of PV panel.
- Estimate the ideality factor n and the saturation current from measured data.
- Plot the measured and calculated dark I-V characteristics.
- Perform a load test on a PV panel.
- Plot the I-V characteristics under different illumination condition.
- Plot the power curves for a PV panel and obtain the maximum power point.
- Determine the Fill Factor and Efficiency if a PV panel.

4. Background

4.1 Photovoltaic History

The history of photovoltaic materials started in 1839 when a French physicist, Alexander Edmund Becquerel, discovered the photo-galvanic effect (Anani, 2013). He observed that electric currents were produced from light induced chemical reactions. Few decades later, other scientists were noticed similar effects in solid “selenium”. However, the first solar cell has been developed with an efficiency of 6% at the late 1940s. The first use of the PV cell was to power a satellite in 1958 and they are still used to power some spacecraft and satellites. Table-1 below provides a short summary about the development of the PV cells (Chaar et. al., 2011).

Table-1: Dates of relevance to photovoltaic solar energy development.

Scientist and innovation	Year
Becquerel discovers the photovoltaic effect.	**1839**
Adams and Day notice photovoltaic effect in selenium.	**1876**
Planck claims the quantum nature of light.	**1900**
Wilson proposes Quantum theory of solids.	**1930**
Mott and Schottky develop the theory of solid-state rectifier (diode).	**1940**
Bardeen, Brattain and Shockley invent the transistor.	**1949**
Charpin, Fuller and Pearson announce 6% efficient silicon solar cell.	**1954**
Reynolds et al. highlight solar cell based on cadmium sulphide.	**1954**
First use of solar cells on an orbiting satellite Vanguard 1.	**1958**

4.2 Photovoltaic Cell Construction

A typical photovoltaic cell is constituted of two separate layers of semiconductor, usually silicon, tightly bonded together as shown in figure-2. N-type is the silicon layer that has excess electrons and P-type is the silicon layer with has excess holes. Sandwiching these layers together generates a PN junction, which is creating an electric field. The free electrons in the N-type material will cross into the P-type material, attempting to fill the electron holes. During this process, the semiconductors layers act as a battery, creating an electric field at the surface where they meet, called "junction". Since holes are move in the opposite direction toward the positive surface. The generated electric field will be in the opposite direction of the natural diffusion. In balance, the current through the PN junction is null (Hecktheuer et. al., 2002).

The "photovoltaic effect" is a basic physical process that converts the sunlight or light into electricity. Light is composed of photons, which are containing various amounts of energy corresponding to the different wavelengths of the solar spectrum. When light (photons) strikes the PV cell surface, some electrons absorb the energy of the photons. In this case, electron will be able to escape from it normal position to become part of the electrical circuit current, which can drive through an external load (Hecktheuer et. al., 2002).

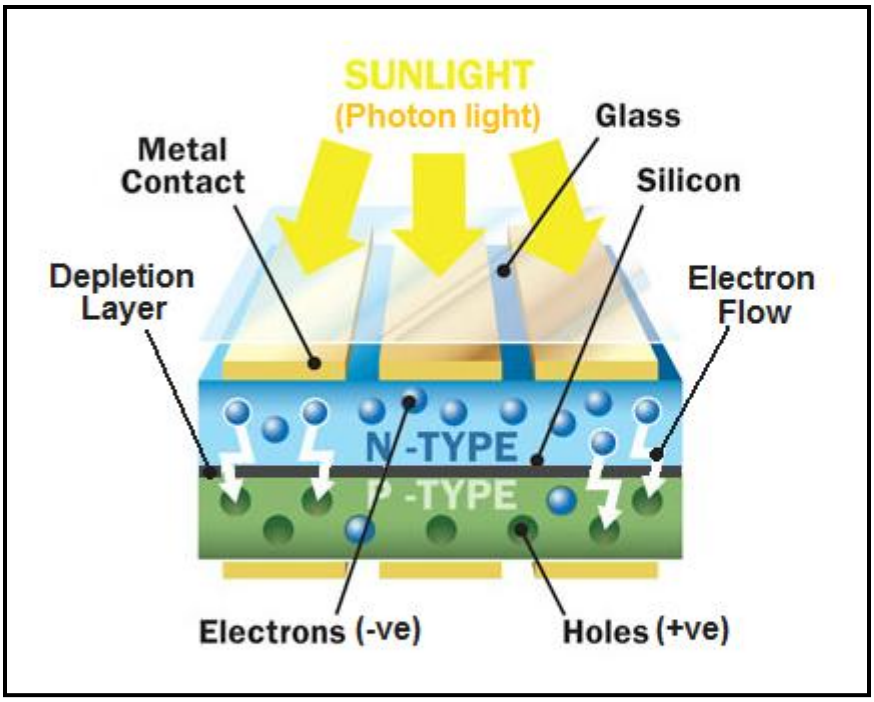

Figure-2: Construction of a PV Cell.

4.3 Photovoltaic Arrays

The PV cell generates small voltage around 0.5 to 0.6V. In order to make a PV module or panel obtain higher voltage, current and power, solar cells can be connected in series and parallel configuration. The number of cells connected in parallel determines the output current of the panel, while the number of cells connected in series determines the panel output voltage (Anani, 2013).

In series configuration a bypass diodes are used to limits the voltage across the shaded PV cell. As shown on figure-3 below, when the bypass diode conduct, it will allow the current from the non- shaded cells to flow to the external circuit. Therefore, the maximum reverse voltage across the shaded cell is going to be reduced to about a single diode drop, so that larger voltage differences cannot arise in the reverse current direction across the cell (Alternative Energy Tutorials, 2013).

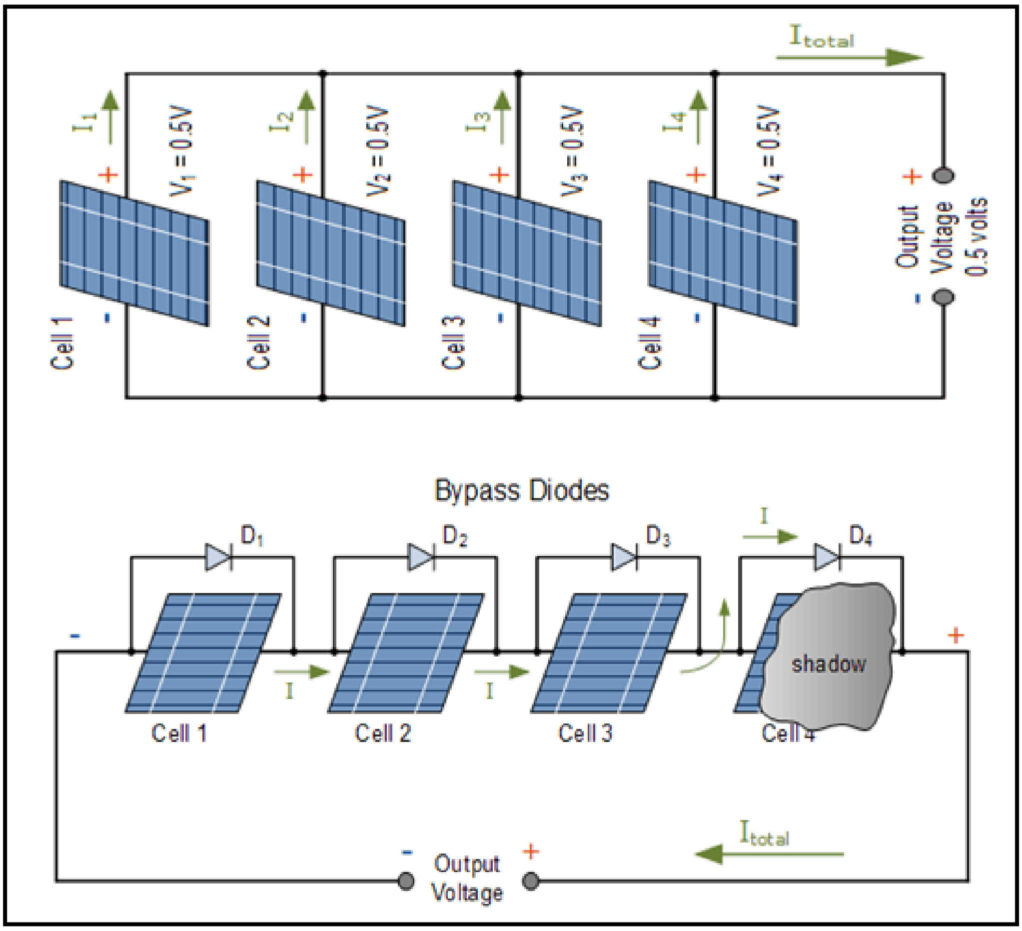

Figure-3: PV arrays parallel and series configuration .

5. Theory

5.1 PV Module Characterization

As shown in figure-4 below, the PV cells can be modelled as a current source in parallel with a diode. If there is no light, the PV cell behaves like a diode. As the intensity of light increases, current is generated by the solar cell.

The I-V characteristic of an ideal solar cell is given by:

$$I_c = I_D - I_{Ph} \tag{1.1}$$

Where I_c is the generated current from the PV cell. I_{ph} is the photo-current generated due to incident light photons and I_D is the diode current, which is given by the following equation:

$$I_D = I_S\left(e^{\frac{qV}{nkT}} - 1\right) \tag{1.2}$$

Where:
k: Boltzmann's constant $k = 1.380x10^{-23}m^2kgs^{-2}K^{-1}$
n: ideality factor
q: electronic charge
V: voltage

At room temperature: $\frac{kT}{q} \approx 25mV = V_T$

V_T: is the thermal equivalent voltage.

The cell equation can be rearranged:

$$I_c = I_S\left(e^{\frac{V_C}{nV_T}} - 1\right) - I_{Ph} \tag{1.3}$$

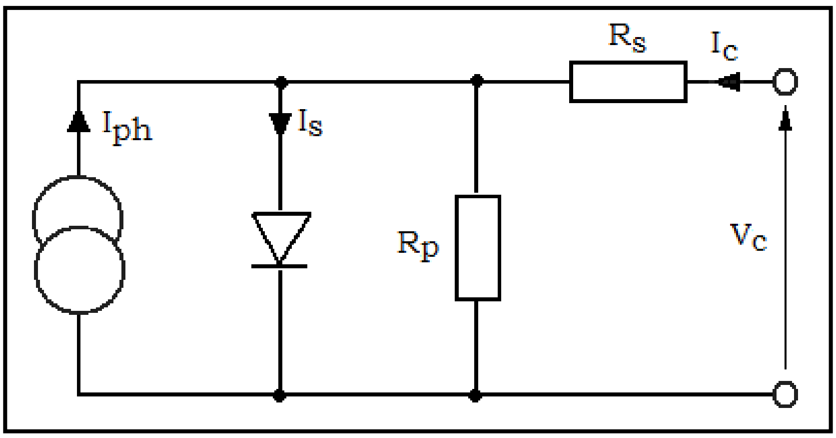

Figure-4: Equivalent circuit of a PV Cell.

An approximate equivalent circuit of the PV cell is shown in figure-4. It is similar to the equivalent circuit of a constant current source. The parallel resistor has negligible effect on the efficiency of the cell and it typically larger than 1kΩ. The series resistance has an adverse effect on the efficiency of the cell and it represents the ohmic contact resistance.

The photocurrent depends on the light intensity striking the surface of PV cell which is given by:

$$I_{Ph} = I_{Ph}\left(G_o\right)\frac{G}{G_o} \tag{1.4}$$

Where G is the sunlight intensity W/m² and Go = 1000 W/m².

The I-V curve of an illuminated solar cell has the shape shown in figure-5. Many performance parameters for the cell can be obtained from this curve.

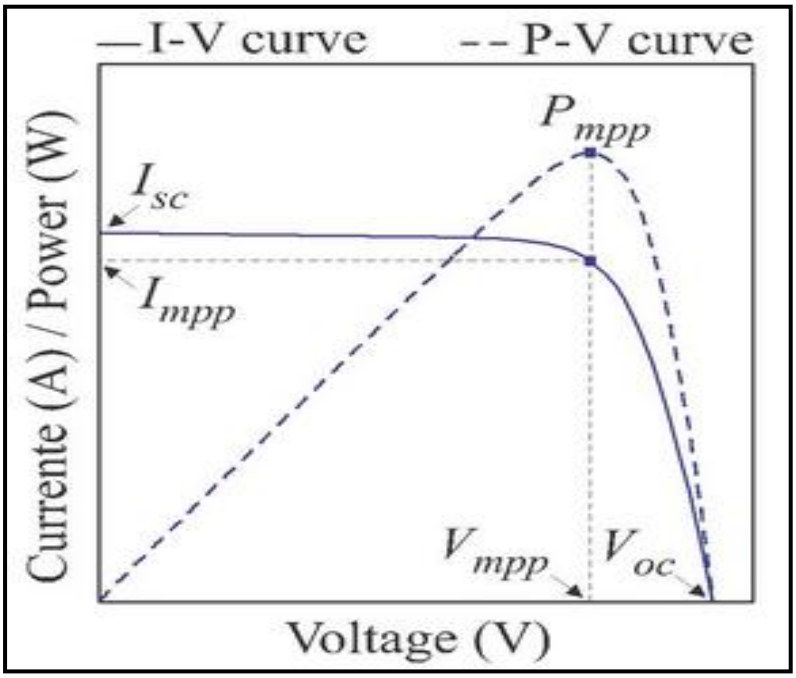

Figure-5: Characterization of a PV Cell.

<u>Short Circuit Current, I_{SC}</u>

This is the current corresponds to the short circuit condition when the impedance is low and is calculated when the voltage equals 0.

$$I(at V = 0) = I_{SC} \tag{1.5}$$

Open Circuit Voltage, V_{OC}

This is the voltage corresponds to the open circuit condition when the impedance is high and is calculated when the current equals 0.

$$V(atI = 0) = V_{OC} \tag{1.6}$$

Assuming that Rp = ∞ and Rs = 0, the shot circuit current and open circuit current can also be obtained using equation (1.2) by putting Ic = 0 and V = 0.

$$I_C = I_{SC} = I_S\left(e^{\frac{0}{V_T}} - 1\right) - I_{Ph} = -I_{Ph} \tag{1.7}$$

$$V_{OC} = \frac{nkT}{q} ln\left(\frac{I_{SC}}{I_S}\right) \tag{1.8}$$

Theoretical Power, P_{Th}

This is the maximum theoretical power, which is would be obtained at the full open circuit voltage and short circuit current.

$$P_{Th} = V_{OC} I_{SC} \tag{1.9}$$

Maximum Power, P_{Max}

This is the actual maximum power point, which represents the area for the small rectangular and it can be obtained using the equation bellow.

$$P_{Max} = V_{MPP} I_{MPP} \tag{1.10}$$

Fill Factor, FF

Fill factor is the ratio of the rectangular areas and it can be calculated using the following formula.

$$FF = \frac{P_{Max}}{P_{Th}} = \frac{I_{MPP} V_{MPP}}{I_{SC} V_{OC}} \tag{1.11}$$

Input Power, P_{in}

The input power is the product of the area of the cell and the irradiance G.

$$P_{in} = aG \tag{1.12}$$

PV Efficiency, η

Fill factor is the ratio of the rectangular areas and it can be calculated using the following formula.

$$\eta = \frac{P_{Max}}{P_{in}} = Maximum\ \eta_{max} \tag{1.13}$$

5.2 Temperature Effects

The PV cells made of semiconductors materials, which are sensitive to temperature. Therefore, the characteristics of the PV cell will vary with temperature, as illustrated on figure-6. As the temperate increases, the short circuit current will increase slightly, while the open circuit voltage will decrease more significantly.

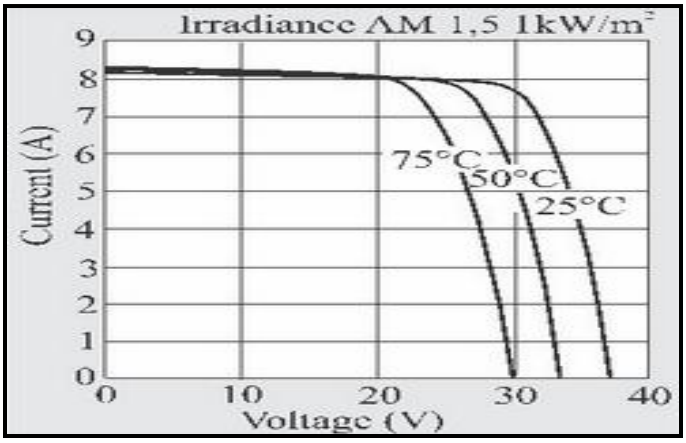

Figure-6: Temperature effects on PV cell.

6. Equipment

- PV panel (Solarix).
- Decade resistance box
- 2 x Digital multimeters.
- Desk lamp
- Light meter.
- Variable DC power supply unit.
- 22Ω resistor

7. Experimental Procedure

7.1 Dark Test

This test is to measure the characterization of the PV cell's resistance and diode properties. The following circuit on figure-7 has been connected. Before switching on the power supply the circuit has been checked and the dc power supply has been set to zero volt. The PV panel has been covered well to keep out any ambient light and then the power supply has turn on. After that, the current I_D has been varied from 0A to 50mA in steps of 5mA through varying the dc supply voltage. At each step, the values of the current I_D and the voltage across the PV panel have been recorded. In order to obtain the values of the ideality factor (n) and the reverse saturation current (Is), the natural logarithm for ID has been calculated and recorded on table-2.

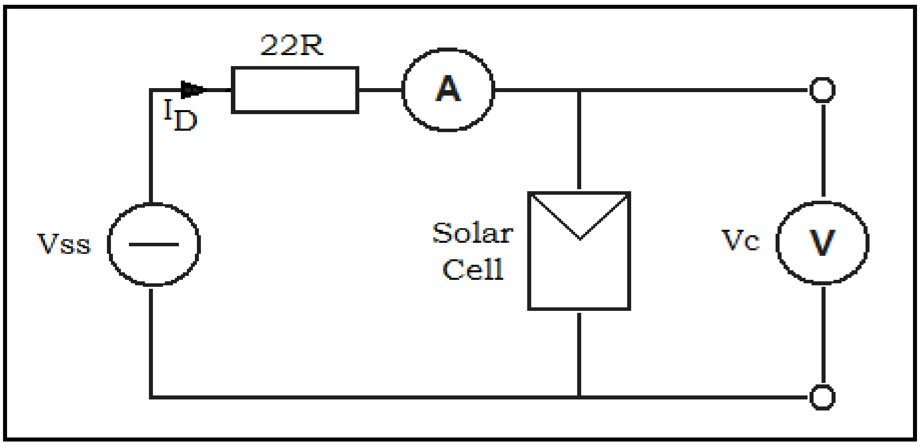

Figure-7: Dark I-V characteristic circuit diagram.

7.2 Illuminations Test

7.2.1 Ambient Light

The circuit on figure-8 below has been connected then the digital light meter probe was placed at the centre of the PV panel in order to measure the ambient light Lo. After recording the ambient light result the digital light meter has been removed without alerting the position of the PV panel. After that, the measurement of open circuit voltage and short circuit current has been recorded. The results can be found in table-3 at the result section.

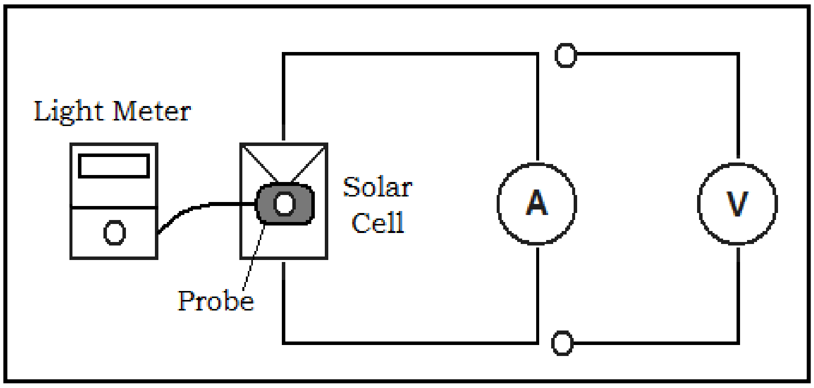

Figure-8: Ambient light I-V characteristic circuit diagram.

7.2.2 Different Illuminations

As shown in figure-9, the desk lamp has been connected to the 230V mains via the dimmer socket. The lamp was placed about 3cm centred above the surface of the PV panel. Then, the lamp was turned on to the maximum illumination (L_{Max}) using the dimmer switch. The light has been measured by placing the digital light probe above the PV panel and the procedure for the pervious part has been repeated and the measurements have been recorded on table-4. Moreover, in order to measure the I-V characteristics for different illuminations, this procedure has been repeated for different lighting levels of approximately 0.1L_{Max}, 0.2 L_{Max}, 0.3 L_{Max}, up to 0.9 L_{Max} all result can be found on table-5.

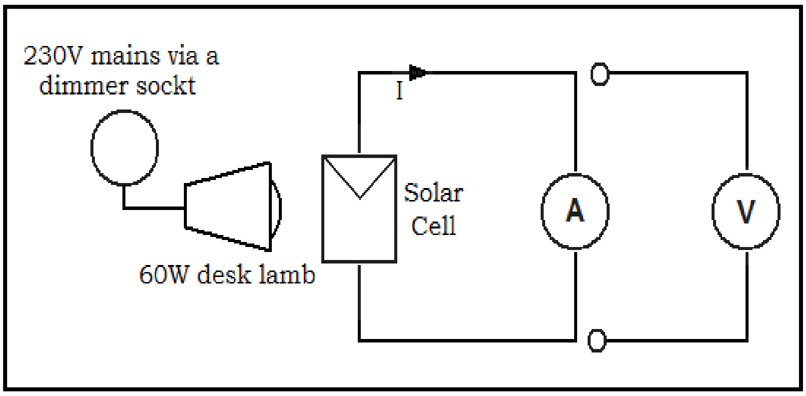

Figure-9: Different illuminations I-V characteristic circuit diagram.

7.3 External Load Test

The following circuit shown in figure-10 has been connected with setting the light level to maximum. Then, the values of illumination (L), open circuit voltage (Voc) and short circuit current, which should be the same as pervious results, has been measured and recorded. After that, the load resistance has been increased from 0 to 1000Ω in steps of 100Ω with recording the load voltage and current at each stage. The same process has been continued until the load resistance reach 2000Ω, but this time with steps of 200Ω. In order to determine the fill factor, the load power will be required; therefore it has been calculated by multiplying the load voltage with the load current. All the results of this part are included in table-6.

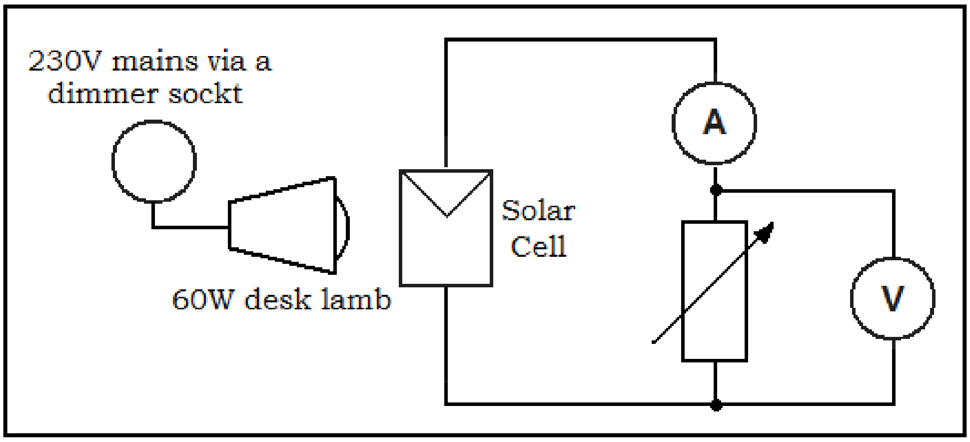

Figure-10: Solar panel with external load.

8. Experimental Results

Table-2: The experimental result of the dark I-V characteristics.

I_D (mA) [experiment]	ln[I_D]	V_{PV} (V)
0	-	0.0634
5	-5.298	5.590
10	-4.605	6.000
15	-4.199	6.224
20	-3.912	6.369
25	-3.688	6.477
30	-3.506	6.563
35	-3.352	6.634
40	-3.218	6.693
45	-3.101	6.743
50	-2.995	6.789

Table-3: The experimental results of the ambient light I-V characteristics.

Lo (lux)	Isc (mA)	Voc (V)
560	0.518	3.48

Table-4: The experimental results of the maximum illumination I-V characteristics.

L_{Max} (lux)	Isc (mA)	Voc (V)
25600	58	6.67

Table-5: The experimental results of the different illumination I-V characteristics.

Lo (lux)	Isc (mA)	Voc (V)
2560	15.37	5.88
5120	23.80	6.15
7680	29.85	6.28
10240	34.10	6.38
12800	40.12	6.41
15360	45.30	6.44
17920	48.74	6.48
20480	55.15	6.45
23040	57	6.49
25600	58.70	6.51

Table-6: The experimental results of the load terminal I-V characteristics.

R (Ω)	I_R (mA)	V_R (V)	P_R (mW) I_R x V_R
0	58.0	0.0001	0.0058
100	50.7	4.90	248
200	29.5	5.65	167
300	20.0	5.82	116
400	15.2	6.91	89.7
500	12.3	6.94	73.1
600	10.3	6.96	61.4
700	8.80	6.98	52.6
800	7.75	6.99	46.4
900	6.87	6.00	41.2
1000	6.13	6.00	36.8
1200	4.78	5.54	26.5
1400	4.11	5.59	23.0
1600	3.62	5.63	20.4
1800	3.27	5.67	18.5
2000	2.94	5.70	16.8

9. Results Analysis and Discussion

9.1 Dark I-V Characteristic

As stated before, the PV panel will behave like a diode, if it completely covered from light. In this case the equivalent circuit of the PV panel will look like the circuit in figure-11. Therefore, a DC power supply was needed to complete the test. From the experimental results provided in table-2, the dark I-V characteristic has been plotted on figure-12. By taking the natural logarithm for the current and plot it against the voltage, the result will be a straight line, see figure-13. The gradient of this line can be use to determine the ideality factor and the saturation current.

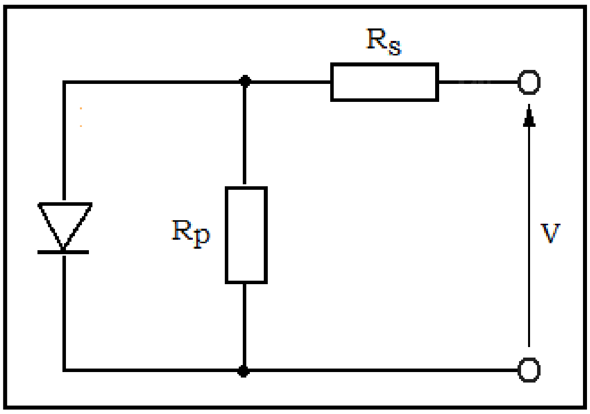

Figure-11: Equivalent circuit for dark test.

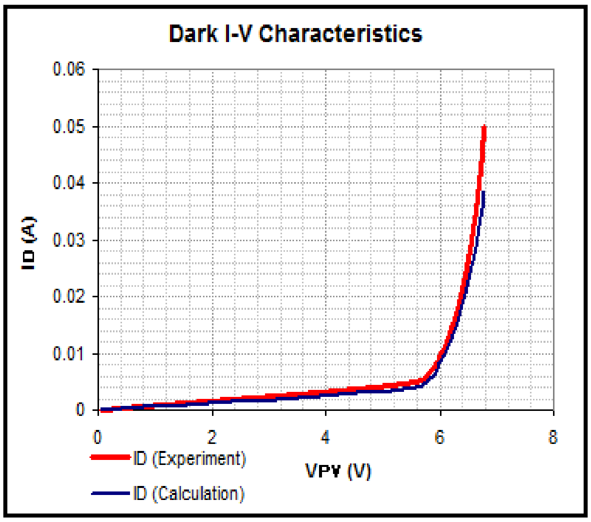

Figure-12: The dark I-V characteristic of the PV cell.

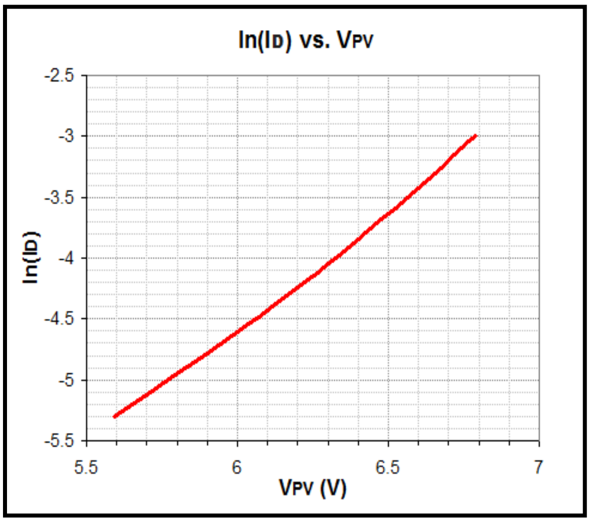

Figure-13: ln(ID) verses the PV voltage.

From equation (1.2):

$$I_D = I_S(e^{\frac{qV}{nkT}} - 1) \qquad \boxed{I_{Ph} = 0}$$

$$I_D = I_S e^{\frac{qV}{nkT}} - I_S$$

$$I_D << I_S$$

$$\therefore \boxed{I_D = I_S e^{\frac{V_C}{nV_T}}}$$

Rearrange to get the linear equation:

$$ln(\frac{I_D}{I_S}) = \frac{V_C}{nV_T}$$

$$\boxed{ln(I_D) = \frac{1}{nV_T} V_{PV} + ln(I_S)}$$

$$y = mx + c$$

<u>The gradient of the slop, m</u>

$$m = \frac{\triangle y}{\triangle x} = \frac{\triangle I_D}{\triangle V_{PV}} = \frac{-3.7 - (-4.6)}{6.48 - 6}$$

$$m = 1.875$$

<u>Ideality Factor, n</u>

$$m = \frac{1}{nV_T} = 1.875$$

$$n = \frac{1}{1.875x25x10^{-3}} = 21.33$$

<u>Saturation Current, Is</u>

$$ln(I_D) = -\frac{1}{nV_T} V_{PV} + ln(I_S)$$

$$ln(I_S) = -\frac{1}{nV_T} V_{PV} + ln(I_D)$$

$$ln(I_S) = -(1.875x6) + (-4.6)$$

$$ln(I_S) = -15.85$$

$$I_S = e^{-15.85} = 0.131 \mu A$$

The current of the cell can be measured by substituting these values in equation (1.2). The calculation result for ID has been recorded in the table below and it plotted on the same graph at the experimental results, see figure-12. It can be clearly seen that both curves are close to each other. The small deference is due to measurement errors.

$$I_D = I_S\left(e^{\frac{V_{PV}}{nV_T}} - 1\right) = 0.131 \times 10^{-6}\left(e^{\frac{V_{PV}}{21.33 \times 25 \times 10^{-3}}} - 1\right)$$

Table-7: The calculated result of the dark I-V characteristics.

V_{PV} (V)	I_D (mA) [calculation]
0.0634	0.000013
5.590	4.01
6.000	8.70
6.224	13.27
6.369	17.45
6.477	21.40
6.563	25.16
6.634	28.76
6.693	32.15
6.743	35.34
6.789	38.54

9.2 Illumination I-V Characteristic

The following graph in figure-14, illustrate the I-V characteristic of the measurement for different light intensity, which is recorded on table-5. The results shows that increase the light intensity will increase both voltage and current. According to what has been discussed before in theory section, the temperature will have a direct effect on the characteristic of the PV module. Placing the desk lamp, which is generates heat, 3cm apart from the PV surface for period of time will causes to increase it temperature, especially when light intensity of the lamb is high or near to maximum. Therefore, the voltage is going to decrease remarkably, while the current is going to increase slightly. The maximum intensity measurement has been taken twice, before and after measuring the lower intensity see table-4 and table-5. The Voc was 6.67V and Isc was 58mA, comparing to Voc was 6.51V and Isc was 58.7mA.

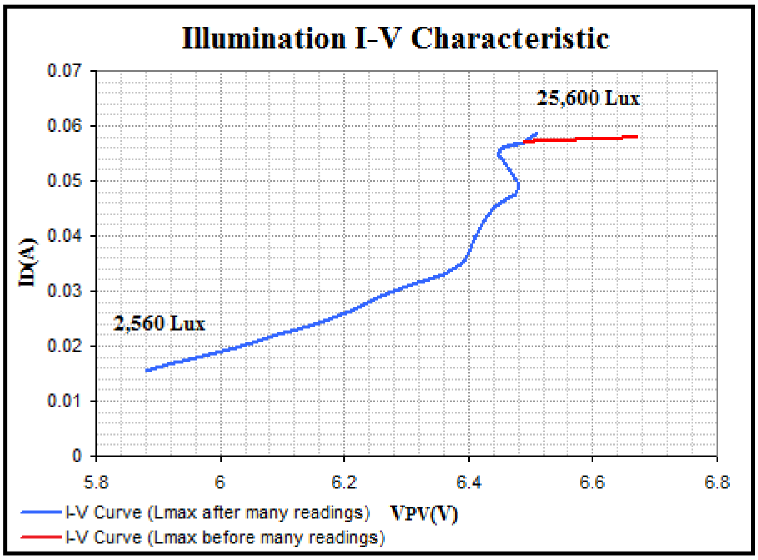

Figure-14: Illumination I-V characteristic.

9.3 External Load Characteristics

The I-V and P-V characteristics for the PV panel have been plotted on figure-14 using the recorded results on table-6. It can be clearly seen that the temperature is also affecting both characteristics. From the calculation below, the efficiency of the solar panel is 6.4%. As the maximum power of the solar panel increases, the efficiency will increase.

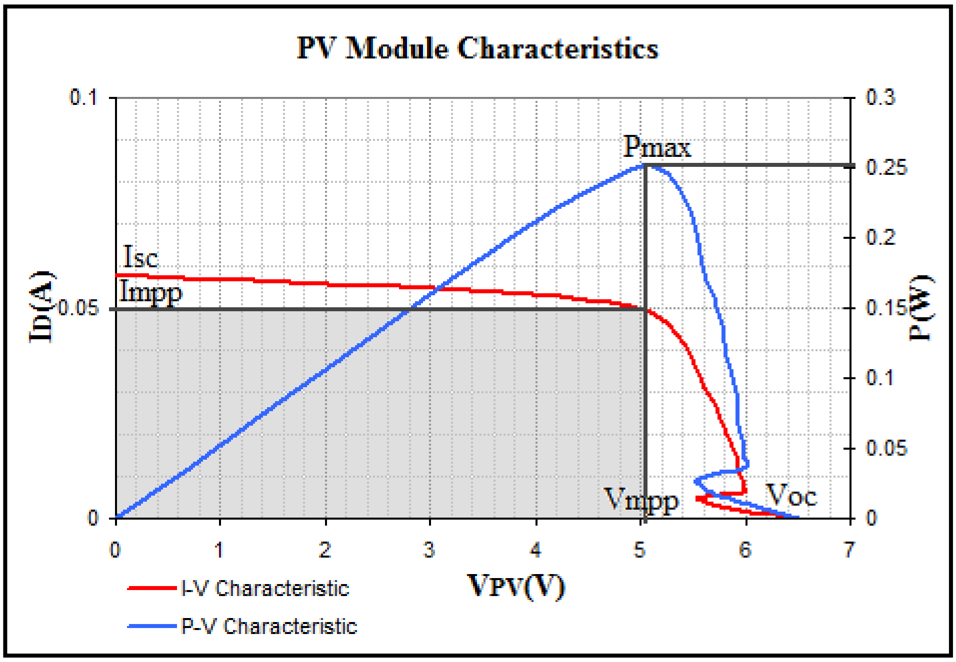

Figure-14: PV module characteristic.

Many important parameters can be obtained from the PV characteristics.

Referring back to the steps on figure-5:

$I_{SC} = 58mA \quad I_{MPP} = 5mA$

$V_{OC} = 6.51V \quad V_{MPP} = 5.05V$

Theoretical Power, PTh

From equation (1.9):

$P_{Th} = V_{OC} \times I_{SC} = 6.51 \times 58 \times 10^{-3}$

$P_{Th} = 0.377\,W$

Maximum Power Point, PMax

From equation (1.10):

$P_{Max} = V_{MPP} \times I_{MPP} = 5.05 \times 50 \times 10^{-3}$

$P_{Max} = 0.2525\,W$

Fill Factor, FF

From equation (1.11):

$$FF = \frac{P_{Max}}{P_{Th}} = \frac{0.2525}{0.377} = 0.67$$

Input Power, Pin

From equation (1.12):

$P_{in} = a \times G = 12 \times 6 \times 10^{-4} \times 500$

$P_{in} = 3.94\,W$

PV Efficiency, η

From equation (1.13):

$$\eta = \frac{P_{Max}}{P_{in}} = \frac{0.2525}{3.94} = 0.064 = 6.4\%$$

10. Conclusion

In conclusion, this laboratory work provides a very good opportunity to understand the behaviour and characteristic of a real PV module. The solar panel has been examined in different situations. At darkness where the PV panel was acting as a diode and it has I-V characteristic of the diode. With deferent illumination, where it acts as a power source depending on the light intensity, as the intensity increases the power increase. Moreover, the PV module characteristics have been determined using a load of variable resistive box. There was a remarkable effect on the solar module because of temperature. However, most important parameters of this module have been obtained.

11. Recommendation

In PV module testing, it is often necessarily to have more than just the I-V characteristic of the module under the test. This experiment shows that temperature has a direct effect on the output power of the PV module. Therefore, a better testing will require making temperature measurement (temp. reference) using thermocouple or any other temperature sensor.

12. Reference

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13. Appendixes

Appendix-1: Solar panel specifications.

Model Number	XHHOO1-4
Max. Power (Pm)	1 W
Unit Size	125x63x3.2 mm
Unit Weight	0.05 kgs
Max. Operating Voltage (Vpm)	6 V
Max. Operating Current (Ipm)	0.166 A
Open Circuit Voltage (Voc)	7.2 V
Short Circuit Current (Isc)	0.183 A
Max. System Voltage	36 V
Number of Cells	12