AL-HUSSEIN BIN TALAL UNIVERSITY

College of Engineering

Department of Mechanical Engineering

SHADING EFFECTS ON PHOTOVOLTAIC ARRAYS OUTPUT: A PROPOSED SOLUTION TO MINIMIZE EFFECT OF SYMMETRICAL SHADE ON PHOTOVOLTAIC SOLAR SYSTEMS

By

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Supervisor

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Dec / 2018

Declaration

I certify that all the material in this thesis that is well referenced and its contents is not submitted, in any other place, to get another certificate.

The contents of this thesis reflect my own personal views, and are not necessarily endorsed by the University.

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Committee Decision

We certify that we have read the present work and that in our opinion it is fully adequate in scope and quality as thesis towards the partial fulfillment of the Master Degree requirements in

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ABSTRACT

One of the main problems that affect the efficient utilization of the power generated by photovoltaic (PV) solar field installed in an area is shading which has been investigated in detail in this thesis. A PV module consist of several cells connected in series or/and parallel, and to prevent complete loss of power of these modules when shade is casted on them, they provided with number of bypass diodes to reduce the effect of shading. However, the current practice is to install PV panels in rows with minimum distance equal to 2h in order to prevent shade casting which will reduce the amount of energy that can be generated from solar filed per unit area of the available land. This thesis presents a proposed methodology for installing the photovoltaic systems in Ma'an city in Jordan that maximize the power generated per unit area of the available land by connecting power generated with time of symmetrical shading on PV rows.

Nine modules of GD-35WP (3.5 watts) were used to investigate the effect of shading when these modules are connected in series or /and parallel to form different configurations. For each configuration, solar irradiation, output voltage, output current, and the cell's temperature were measured. Furthermore, in order to simulate the effect of shade on solar filed generated power. It was assumed that a solar filed with 120 kWp need to be designed using Canadian solar module SUPERPOWER CS6K- 300. The module power is 300W, and therefore 400 modules were required and arranged in 20 strings with 20 modules per each string.

It was found that the reduction in array output power by symmetrical shading is affected by number of modules and array geometry, and it is recommended to use rectangular panels with number of rows (m) larger than columns (n), and in this case, the power will be reduced by 1/m instead of 1/n. However, increasing number of rows will increase the length of the panel, which causes the array shade longer, and this has the opposite effect.

It was also found that if the time of the year when shade cast on rows is carefully determined, reducing the horizontal distance between rows even to the degree of shading will improve the area utilization factor and electric energy per unit of the available land. In this thesis, it was shown that reducing the distance between rows to 1.6h improved area utilization factor and the generated electric energy per unit of the available land by 11.3% and 11.1% respectively.

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List of abbreviations

ppm: parts per million

TPES: total primary energy supply

BP: British petroleum

CIGS: copper indium gallium selenide

V_{oc}: open circuit voltage (V)

I_{sh}: short circiuit current (A)

I_{ph}: photocurrent (A)

I_D: diode current (A)

K_i: short circuit current of cell at 25□C and 1000 W/m^2

T: operating temperature (K)

I_r: solar irradiation (A)

I_0: module saturation current (A)

I_{rs}: module reverse saturation current (A)

T_r: nominal temperature (K)

N_s: number of cells connected in series

N_p: number of cells connected in parallel

V_t: diode thermal voltage (V)

V'oc: open circuit voltage under different values of irradiation (V)

STC: standard test conditions

FF: fill factor

BTU: British thermal unit

Nn: Nano meter

PLF: power land factor

UF: area utilization factor

1. CHAPTER 1: INTRODUCTION &LITERATURE REVIEW

1.1 General Introduction

There are several driving forces for the increase usage of renewable energy nowadays, environmental, economic, or in some cases national security related aspects. The greenhouse gas emissions are on the top of the environmental issues, and the most harmful greenhouse gas is carbon dioxide, which its atmospheric concentration is affected by human activities, in deed, the atmospheric CO_2 concentration has risen from about 275 ppm to about 400 ppm (Mathews, 2014).

Energy demand has increased recently due to worldwide economic growth. Measured as total primary energy supply (TPES), global energy demand that still mainly relies on fossil fuel, increased by almost 150% between 1971 and 2015. In 2015, two sectors have produced two-thirds of global CO_2 emissions; fuel combustion for electricity and heat generation, which accounts for 42%, and transport accounting for 24% (OECD/IEA, 2017).

British Petroleum (BP) statistical review of World Energy published in 2017 showed that the global primary energy consumption increased by just 1% in 2016; meanwhile 0.9% and 1% growth were reported in 2015 and 2014, respectively, in comparison with 10-year average of 1.8% a year (British_Petroleum, 2017). The worldwide electricity generation has increased from 21.6 trillion kilowatt-hours (kWh) in 2012 to 25.8 trillion kWh in 2020, and it is expected to reach 36.5 trillion kWh in 2040 (EIA, 2016). Therefore, to reduce the amount of CO_2 emissions, renewable energy technologies should be adapted.

Solar photovoltaic systems, which exists in both domestic and commercial scales, are one of the most promising renewable energy technologies nowadays. During 2016, the investment capacity in this sector reached 303 GW (REN21, 2017). Several photovoltaic cells and modules technologies currently available in the market such as monocrystalline, polycrystalline, thin films, and copper-indium-gallium-selenide (CIGS) technology, etc. (Bagher, et al., 2015). Photovoltaic system harvest sun irradiation and turns it into direct current, and the yield of such system defined by how much watts the system can generate per unit area depends on several parameters such as type of photovoltaic cells, irradiation, wind speed, photovoltaic cells orientation, and shading (Verma & Singhal, 2015). Photovoltaic models are usually connected in series to form a string; the strings connected in parallel with other strings to form an array, shading any part of the array significantly affect PV system power output (Zegaoui, et al., 2011). Therefore, it is a common practice to increase the distance between PV system rows to prevent shading (Kong, et al., 2015); however, this will reduce the amount of power produces per unit area of land, which increase the capital cost of PV system especially if the land is expensive.

In this master thesis, a polycrystalline module was used to study the effect of shading on the module output power and to connect this drop with the distance between adjacent rows to find the optimum distance that produce the maximum power per unit area of the land. This thesis is organized as follows: in the first chapter, a state-of-the-art literature review about mathematical representation of PV cells and the relation between shading and voltage and current of PV array. The second chapter discussed a detailed description of equipment used in the study, and detailed illustrations of experimental design, while in the third chapter a comprehensive analysis of the data were presented. Finally, conclusions and recommendation will be presented in chapter 4.

1.2 Literature review

1.2.1. Modelling and mathematic representation of photovoltaic cell

The basic element in the photovoltaic system is the solar cell, which is an electronic device that converts the photon energy into direct electrical energy. Figure 1-1 shows a representation of photovoltaic cell where V is the output voltage of the cell and I its output current. The equivalent series resistance of the cell is represented by Rs while R_{sh} is the cell shunt resistance. On the other hand, the current passes through the shunt resistance is I_{sh}, and the current passes through the diode is I_D.

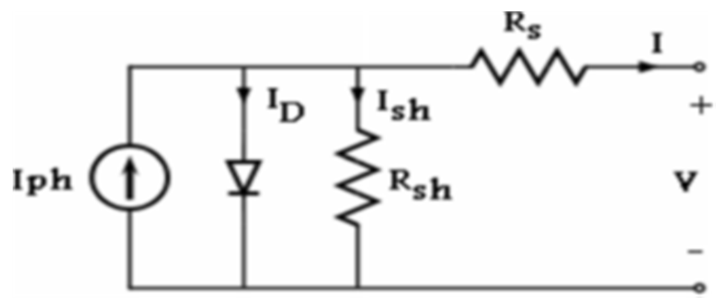

Figure 1-1 Photovoltaic equivalent circuit (Nguyen & Nguyen, 2015)

The value of voltage and current produced by a single PV cell is very small, and therefore PV cells are connected either in series or/and parallel to generate larger values of

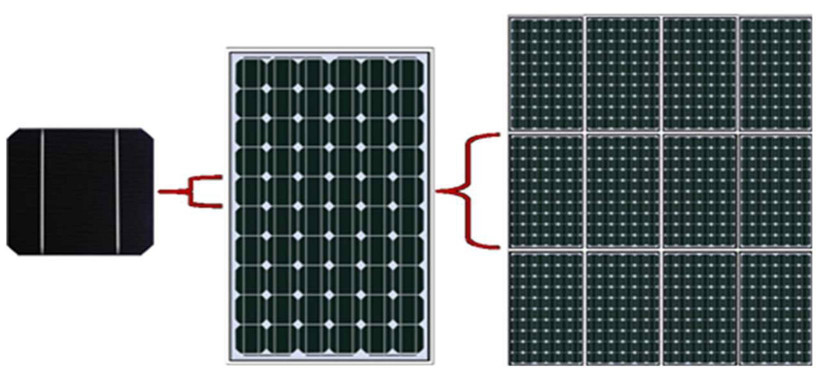

Figure 1-2 Solar cell module and array

voltage and current which will in turn resulted in higher values of power. Connecting solar cells together is called solar module while connecting them in series is a string. An array of solar cells is produced as shown in figure 1- 2 if strings are connected in parallel.

Using circuit analysis techniques (figure 1- 3), the following equations for a PV array open circuit voltage (V_{OC}) and short circuit current (I_{sc}) can be derived as follows (Nguyen & Nguyen, 2015):

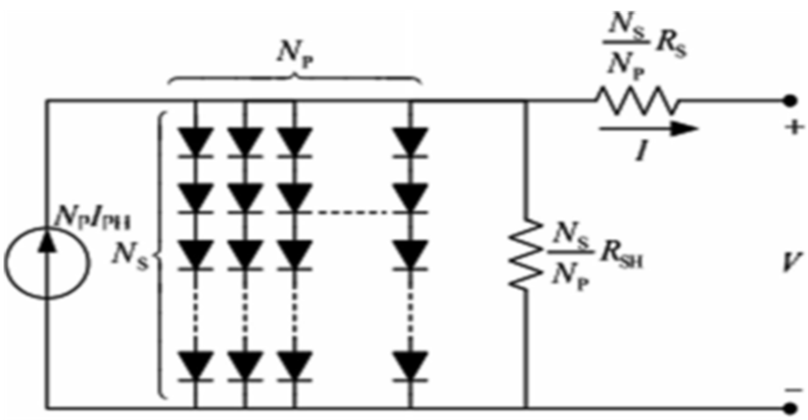

Figure 1-3 Equivalent circuit of solar array (Nguyen & Nguyen, 2015)

At the output side, the output current I can be found by (Nguyen & Nguyen, 2015)

$$I = I_{ph} - I_D - I_{sh} \tag{1.1}$$

Where: I_{ph} is the photocurrent measured in (ampere) (Nguyen & Nguyen, 2015)

$$I_{ph} = [\, I_{sc} + K_i(T - 298) \times \frac{Ir}{1000} \tag{1.2}$$

Here, Isc: is the short circuit current (A) for the cell; Ki: short-circuit current of cell at 25°C and 1000 W/m^2; T: operating temperature (K); and Ir is the solar irradiation (W/m^2);

The diode current (I_D) is given by equation 1.3 (Nguyen & Nguyen, 2015)

$$I_D = I_o[e^{\frac{\frac{V}{N_S}+\frac{IR_S}{N_p}}{n \times Vt}} - 1] \tag{1.3}$$

$$I_o = I_{rs}[\frac{T}{T_r}]^3 \times e^{\frac{q \times E_{go}}{n \times k}(\frac{1}{T} - \frac{1}{T_r})} \quad (1.4)$$

I_0; the module saturation current

I_{rs}: module reverse saturation current: (Nguyen & Nguyen, 2015)

Tr: nominal temperature = 298.15K

$$I_{rs} = \frac{I_{sc}}{e^{\frac{q \times V_{oc}}{N_s \times k \times n \times T}} - 1} \quad (1.5)$$

Here, q is electron charge which equals to 1.6×10^{-19} C; Voc: open circuit voltage (V); Ns: number of cells connected in series; n: the ideality factor of the diode; and k: is Boltzmann's constant, = 1.3805×10^{-23} J/K. (Nguyen & Nguyen, 2015)

$$I_{sh} = \frac{V \times \frac{N_p}{N_s} + I \times R_s}{R_{sh}} \quad (1.6)$$

$$V_t = \frac{k \times T}{q} \quad (1.7)$$

Where Np is the number of PV modules connected in parallel; Rs: series resistance (Ω); Rsh: shunt resistance (Ω); while Vt: is diode thermal voltage (V).

Finally, substitute these equations into equation (1.1) will give the general equation for PV array current: (Nguyen & Nguyen, 2015)

$$I = N_p \times I_{ph} - N_p \times I_o \times \left[e^{\frac{\frac{V}{N_s} + I \times \frac{R_s}{N_p}}{n \times V_t}} - 1 \right] - I_{sh} \quad (1.8)$$

Equation 1.8 shows that PV array current depends on I_{ph} which in turn depends on irradiance (W/m^2) from the sun. On the other hand, equation 1.9 shows that the open circuit voltage Voc increases logarithmically with light intensity. In addition, equation 1.10 shows the effect of irradiation on the open circuit voltage; (V' oc) per cell under different values of irradiation (Tobnaghi, et al., 2013).

$$V_{oc} = \frac{n \times k \times T}{q} \times \ln\left(\frac{I_{ph}}{I_o} + 1\right) \tag{1.9}$$

$$V'_{oc} = V_{oc} + \frac{n \times k \times T}{q} \times \ln\left(\frac{I_r}{1000}\right) \tag{1.10}$$

1.2.2. The Current – Voltage relationship curve

The current – voltage curves show the behavior of PV module and string under certain operating conditions such as temperature, irradiation, number of series and parallel connections, etc. Figure 1- 4 shows a typical current – voltage curve and power – voltage curve plotted based on the data sheet of GD-35WP module (appendix B. is a sample of Matlap code used to plot I-V and P-V curve for PV). Here, in figure 1- 4, it is important to know that this curve was plotted under standard test conditions (STC) which states that of irradiance of 1000 W/m^2, spectrum Air Mass 1.5 and cell temperature of 25°C (Standards, 2010).

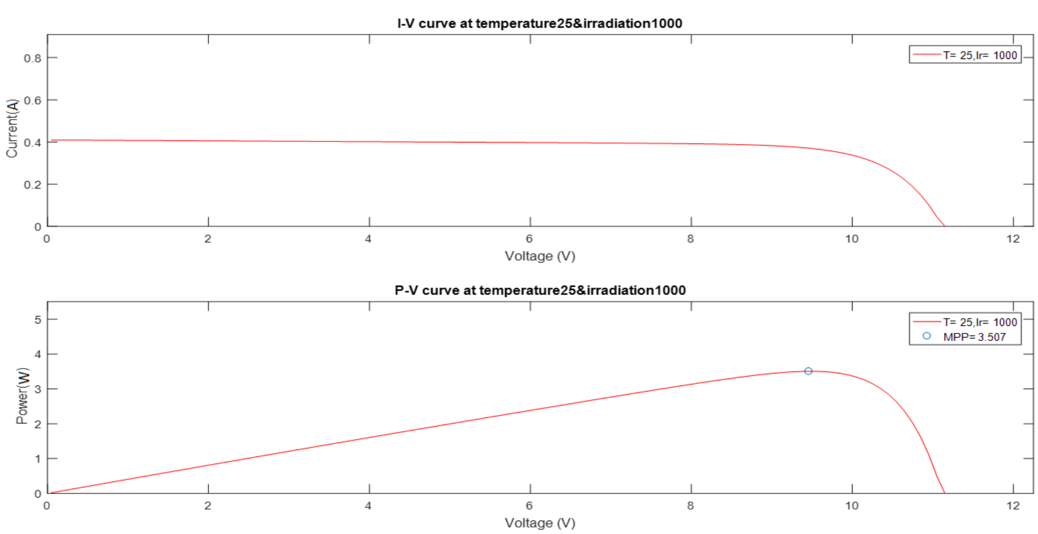

Figure 1-4 Current (I) -voltage (V) and power (P)-voltage (V) curves; MPP is maximum power point

Figure 1.4 shows that the maximum current (Isc) occurs when the voltage is zero while the maximum voltage (Voc) occurs when the current is zero. The figure shows that there is an optimum load where the power is maximum, and this point is called the maximum power point. A factor called fill factor (FF) is defined, therefore, to compare the maximum power with PV power at short circuit current (Isc) and open circuit voltage (Voc) as shown in equation 1.11. The fill factor decreases with temperature and its value for a typical cell is 0.7 (Amelia, et al., 2016).

$$FF = \frac{P_{max}}{I_{sc} \times V_{oc}} = \frac{I_{max} \times V_{max}}{I_{sc} \times V_{oc}} \qquad (1.11)$$

On the other hand, increasing solar radiation at constant temperature will increase PV output current and voltage, as shown in figure 1-5, the current has increased linearly while voltage and power increased exponentially. Figure 1-6 shows that PV cell temperature has a deteriorating effect on the cell voltage while the output current was almost constant. Therefore, temperature linearly decreases the PV power (Arjyadhara & Chitralekha, 2013).

In series PV connection, as shown in figure 1-7, the array output current is equal to the current of the cell while the voltage is equal to the summation of each cell while total output powers equals to power summation irrespective of the connection of the cells.

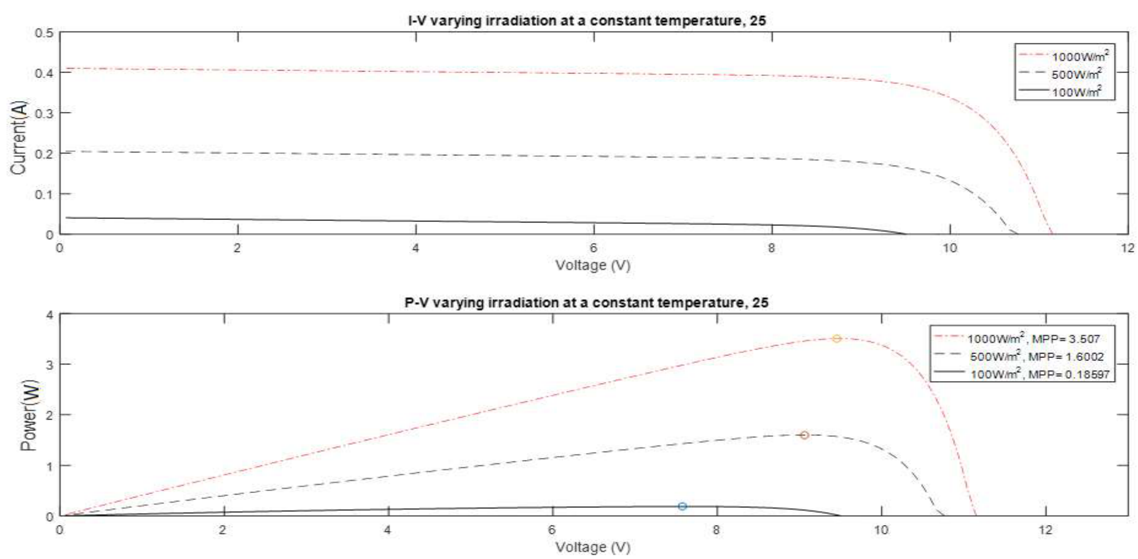

Figure 1-5 Effect of irradiation on I-V and P-V curves.

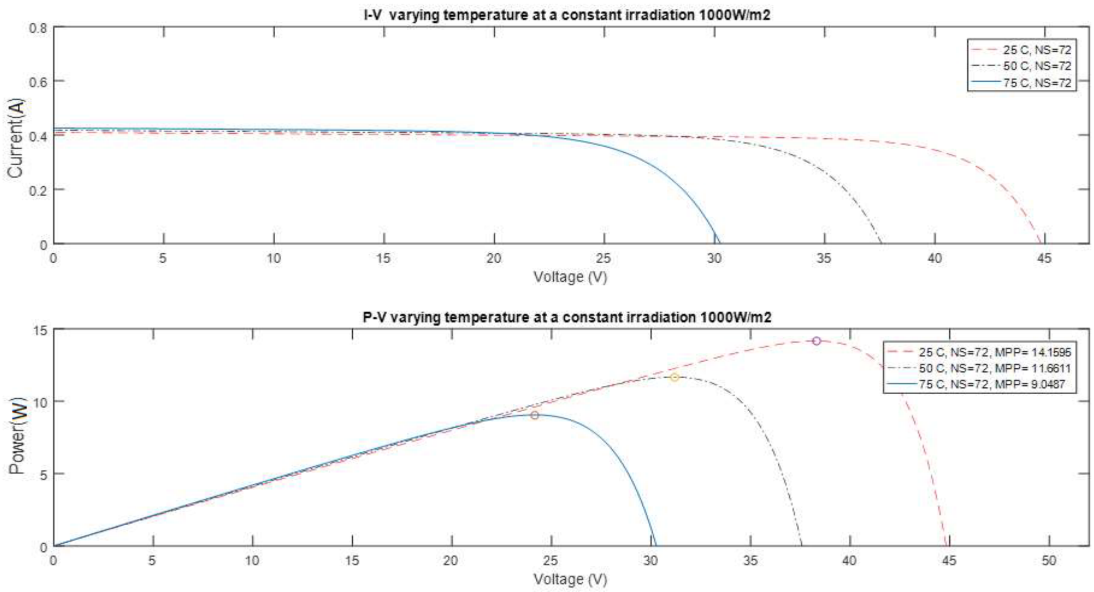

Figure 1-6 Effect of temperature on I-V and P-V curves.

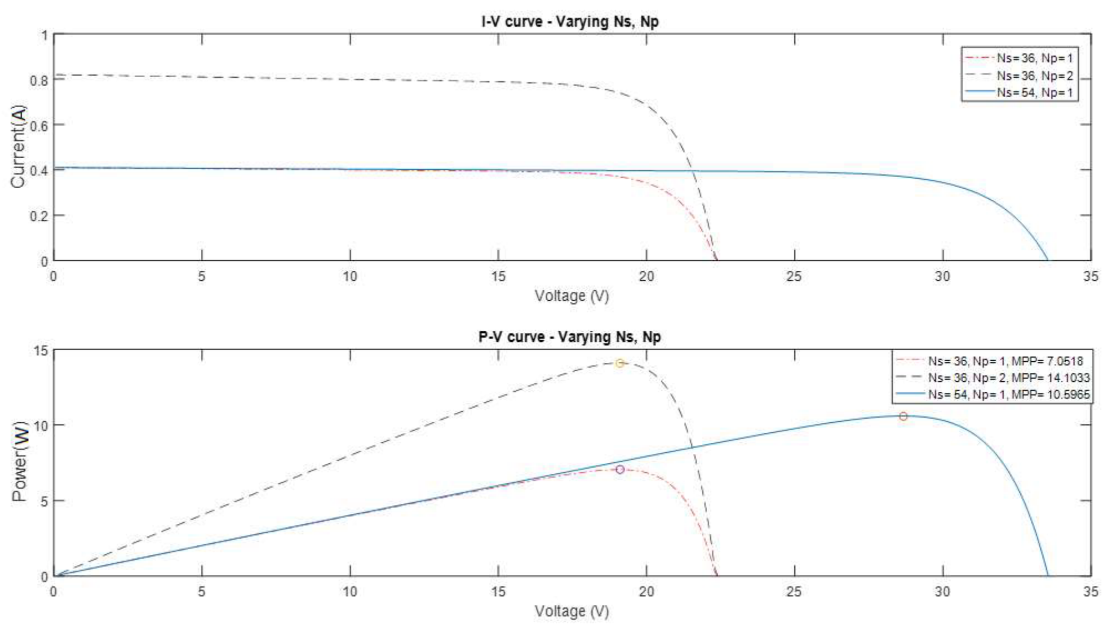

Figure 1-7 Effect of type of connection on I-V and P-V curves.

Analyzing previous equations 1.1-1.10 and figures 1-4 to figure 1-6 reveals that the relationship between the output voltage and current are changing with temperature, irradiation, number of cells connected in series/parallel combinations. Some of these parameters affect voltage more than current and vice versa, but in each case, the array output power will be affected.

1.3 Shading effects on photovoltaic cell / module / array and bypass diode

As shown previously, Figure 1-1 shows the equivalent circuit of a single PV cell while figure 1-8, shows a series connection of two photovoltaic cells. Figure 1-9 illustrate shaded equivalent circuit, current produced by the unshaded cell (b) need to pass through the shaded one (b) which current is zero ($I_{ph} = 0$), and since the shunt resistance is very large, no current will pass through it (Dwivedi, et al., 2016). Therefore, the string becomes an open circuit and the current is lost. To overcome this problem, a bypass diode is added to the string as shown in figure 1-10 which passes the current in case the cell a is shaded (Pannebakker, et al., 2017).

In figure 1-8, the power of the array without bypass diode is $V_{op} \times I_{sc}$ while the power of the shaded array in figure 1-9 is zero since the $I_{sc} = 0$. On the other hand, the power of the shaded array with diode bypass as shown in figure 1-10 is $\frac{1}{2} V_{op} \times I_{sc}$ since the array voltage will be for one PV cell only; hence, by using bypass diode 50 % of the array power is saved (Teo, et al.,2017).

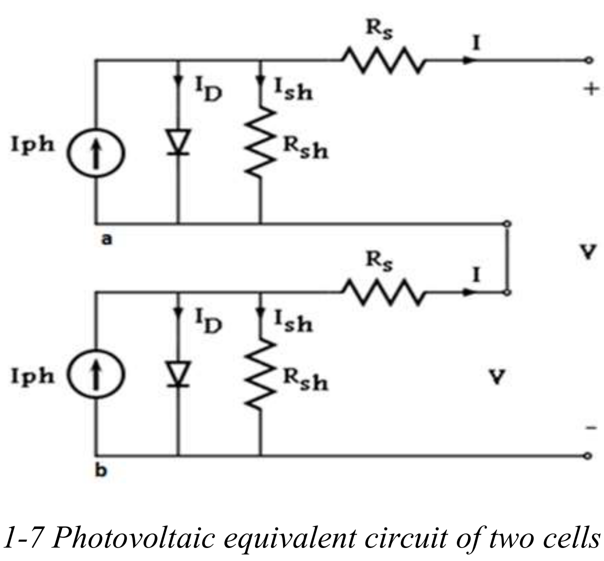

Figure 1-7 Photovoltaic equivalent circuit of two cells in series.

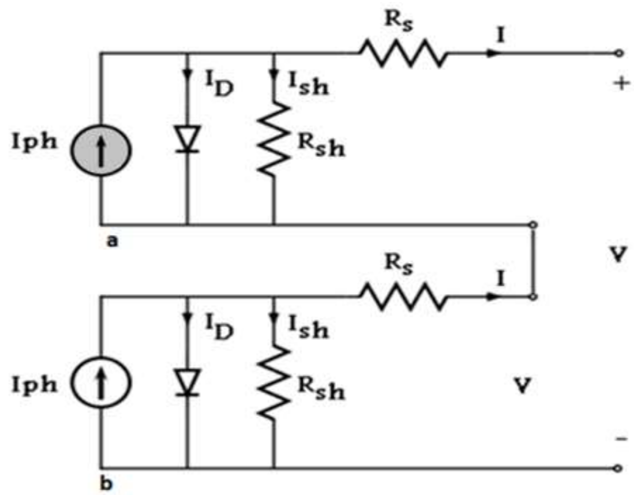

Figure 1-8 Photovoltaic equivalent circuit of two cells in series. One cell was shaded

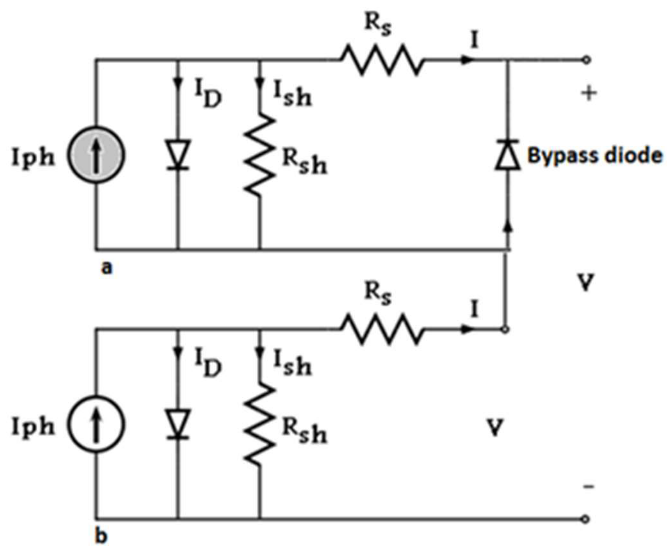

Figure 1-9 Photovoltaic equivalent circuit of two cells in series with bypass diode.

Figure 1-11, shows I-V curve for a PV array with 36 V open circuit voltage, 9.5A short circuit current, and rated power 342 W. Assuming power factor of 0.7 as shown in equation

1.11 the array maximum power is about 239 W. When only three bypass diodes are used, the maximum out power is 108 W, which is the 32% of its rated power. Increasing number of bypass diodes will increase the array output power, and when 60 bypass diodes are used, the array power is 230W, which is 70% of the rated array power. Therefore, understanding the interconnection between photovoltaic modules is a necessary in order to determine number of bypass diodes, which minimizes the power losses (Rooijakkers, 2016).

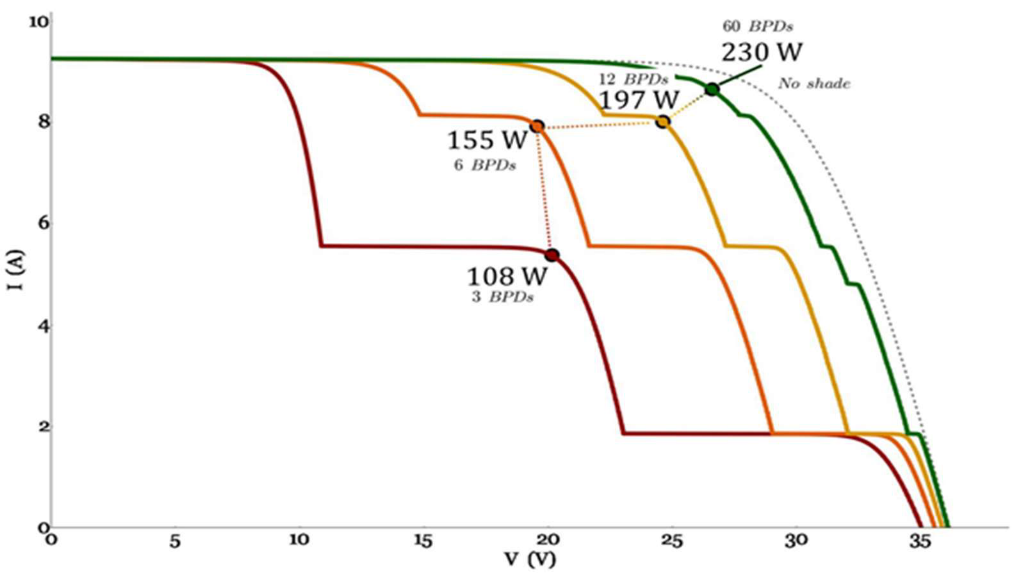

Figure 1-10 The I-V curve under shading with different number of bypass diodes (Rooijakkers, 2016)

1.4 Photovoltaic cells / modules connection

A photovoltaic cell has an output voltage range between (0.5-0.8 volts) which is not enough for most applications (Nayan & Ullah, 2015). Nevertheless, the photovoltaic output power for photovoltaic systems may ranges from few watts to megawatts, which makes PV systems suitable for any application.

There is no one configuration for connecting photovoltaic cells/ modules exists because it depends on module specification and application. The output ranges for voltage and current can be controlled by setting number of cells/ modules connected in parallel and/ or in series.

Table 1-1 refers to a small photovoltaic module with only 3.5 watts. Connecting two modules in series at STC produces total output 18V (Vmp) and 0.38A (Imp) while connecting them in parallel produces total output 9V (Vmp), and 0.76A (Imp).

Table 1-1 Electrical data for GD-35WP module at STC (GDLITE, 2017)

Nominal Max. Power (Pmax)	3.5 W
Opt. Operating Voltage (Vmp)	9 V
Opt. Operating Current (Imp)	0.38 A
Open Circuit Voltage (Voc)	11.25 V
Short Circuit Current (Isc)	0.41 A

1.4.1. Methods of installing photovoltaic modules

It is important to study the site before installing the photovoltaic system; some considerations need to be taken into account for planning the site. The average ambient temperature needs to be determined because of its negative impact when it rises as shown previously. In addition, the nearby obstacles, which block the irradiation from the sun and cast shadow on the photovoltaic modules, need to be taken in consideration. Also, the available area where the photovoltaic system will be installed need to be determined (Noorollahi, et al., 2016).

In a power generation plant using photovoltaic systems, groups of photovoltaic modules are connected, and the number of series/ parallel modules to be connected are limited by the input parameters and the size of the inverter. The input voltage range for the inverter limits number of modules in series (called string), while the input parameter of the current does limit number of modules / strings connected in parallel (called array) (Kerekes, et al., 2013). Therefore, to ensure the performance of the photovoltaic system, it is important not to have a mismatch between the output of the photovoltaic string/ array and the input parameters of the inverter.

1.5 Solar angles and module orientation

As shown previously the irradiation of the suns ray is very important for generating power using the photovoltaic systems. In this section, we will have a look at the angles of PV installations and its relationship with irradiation reaches photovoltaic cells/ modules.

It is important to study the path of the sun in the sky, and it is convenient to assume that the sun is moving with respect to the earth. Tracking the sun in the sky is a straightforward process, but before explaining the tracking process the following angles need to be defined; they are declination angle, hour angle, solar altitude angle, solar azimuth angle, and incident angle as shown in figure 1-12. (Kalogirou, 2014)

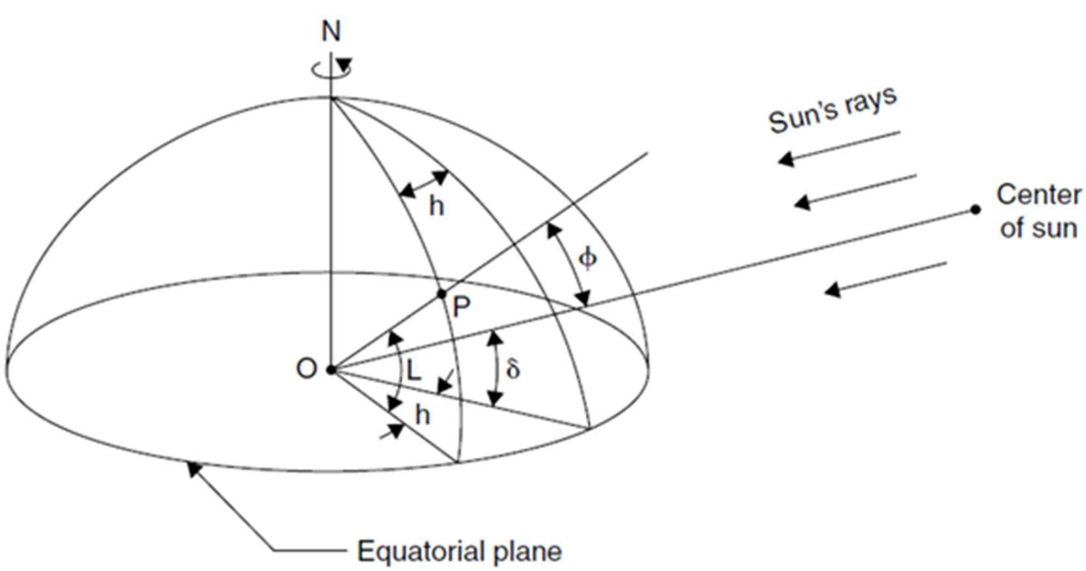

Figure 1-11 Definition of latitude, hour angle, and solar declination. (Kalogirou, 2014, p. 54)

1.5.1. Declination angle (δ)

Declination angle is the angle between the sun-earth centerline and the projection of this line on the equatorial plane. The declination, in degrees for any day of the year (N) can be calculated approximately by the equation (1.12). (Kalogirou, 2014, p. 54)

$$\delta = 23.45 sin\left[\frac{360}{365}(284 + N)\right] \quad (1.12)$$

Where N is the number of the day during the year.

1.5.2. Hour angle (h)

The hour angle, (h), of a point on the earth's surface is defined as the angle through which the earth would turn to bring the meridian of the point directly under the sun. Because the sun transverse each 15^0 longitude in one hour, the hour angle at each minute from solar noon is given by equation 13.1. (Kalogirou, 2014, p. 56)

$$h = \pm 0.25 \text{ (Number of minutes from local solar noon)} \quad (1.13)$$

1.5.3. Solar altitude angle (α)

The solar altitude angle (α) is the angle between the sun's rays and a horizontal plane. It is related to the solar zenith angle, Φ, which is the angle between the sun's rays and the vertical.by $\Phi + \alpha = \frac{\pi}{2}$

$$\sin(\alpha) = \cos(\emptyset) = \sin(L)\sin(\delta) + \cos(L)\cos(\delta)\cos(h) \quad (1.14)$$

Where L= local latitude, defined as the angle between a line from the center of the earth to the site of interest and the equatorial plane. (Kalogirou, 2014, p. 58)

1.5.4. Solar azimuth angle (z)

The solar azimuth angle, (z), is the angle of the sun's rays measured in the horizontal plane from due south (true south) for the Northern Hemisphere or due north for the Southern Hemisphere; westward is designated as positive. The mathematical expression for the solar azimuth angle is (Kalogirou, 2014, p. 58)

$$\cos(z) = \frac{\sin(\alpha)\sin(L) - \sin(\delta)}{\cos(\alpha)\cos(L)} \tag{1.15}$$

1.5.5. Incidence angle (θ)

The solar incidence angle, (θ), is the angle between the sun's rays and the normal on a surface, and it is calculated by the following equation. (Kalogirou, 2014, p. 60)

$$\cos(\theta) = \sin(L)\sin(\delta)\cos(\beta) - \cos(L)\sin(\delta)\sin(\beta)\cos(Zs) + \cos(L)\cos(\delta)\cos(h)\cos(\beta) + \sin(L)\cos(\delta)\cos(h)\sin(\beta)\cos(Zs) + \cos(\delta)\sin(h)\sin(\beta)\sin(Zs) \tag{1.16}$$

Where; β = surface tilt angle from the horizontal

Z_s = surface azimuth angle, the angle between the normal to the surface from true south, westward is designated as positive.

Applying equation 1.16 in a tilted surface as shown in figure 1-13, the following cases can be produced:

- For a horizontal surface, β = 0 and $\theta = \Phi$
- For a vertical surface, β = 90
- For a south-facing, tilted surface in the northern hemisphere, Z_s=0

However, for a moving surface that tracking the sun in both axes, horizontal and vertical axis tracking, the surface should face the sun all time during the day which can be achieved by making the incident angle equals to zero degrees (θ=0).

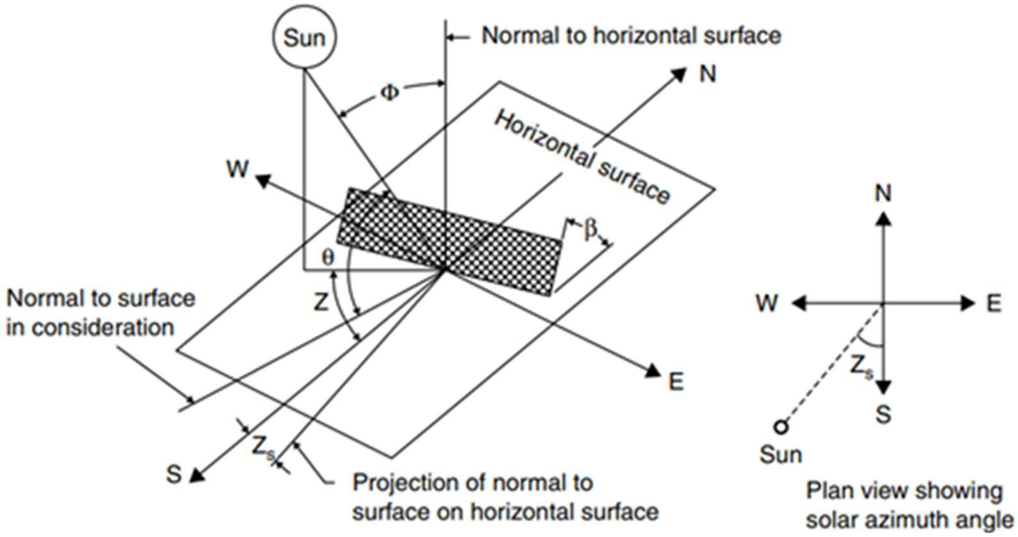

Figure 1-12 Solar angles on a tilted surface (Kalogirou, 2014, p. 61)

1.6 Sun path diagrams

Sun path shows the position of the sun in the sky by reading solar azimuth and altitude angles directly from the diagram during all days in a year. Sun path diagram has different types, and the most popular are shown in figure 1-14 and 1-15, respectively.

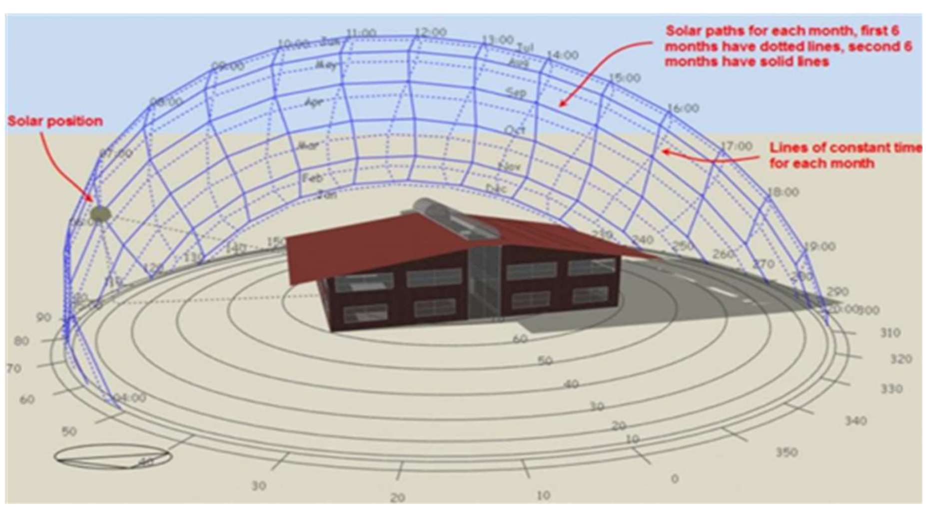

Figure 1-13 3-D sun path diagrams (Smith, 2017)

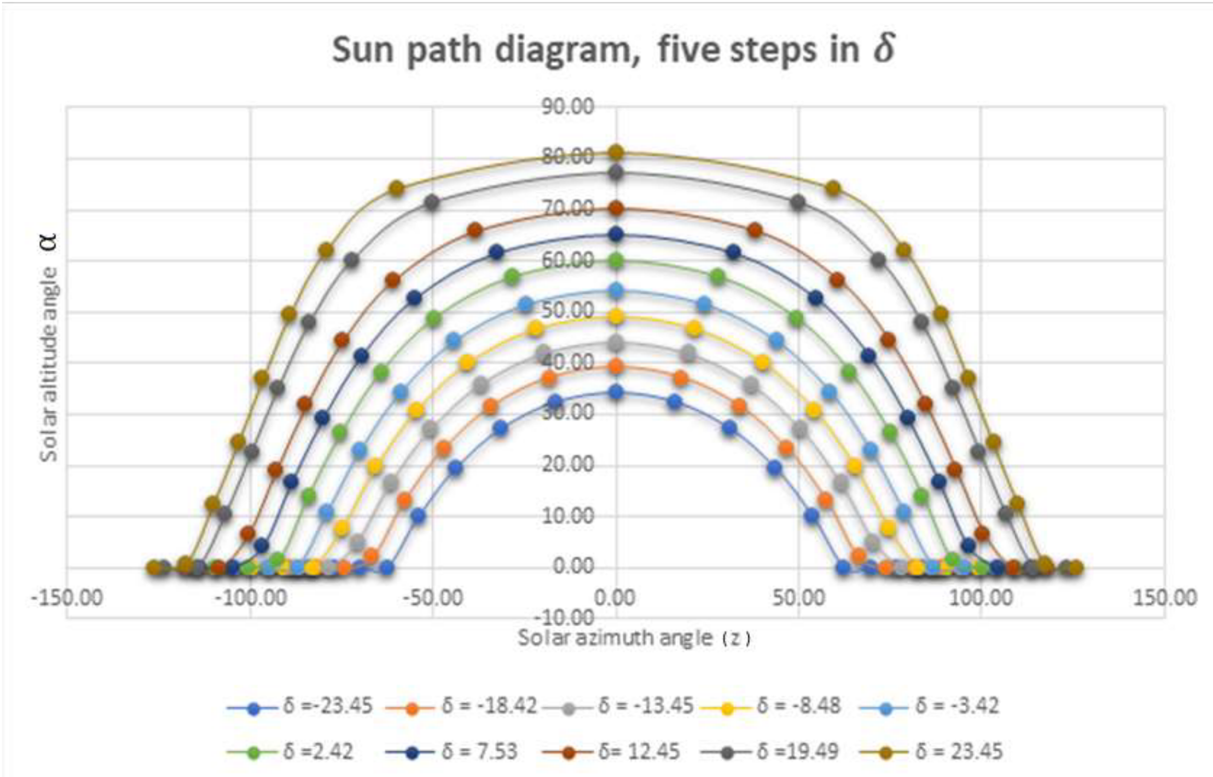

Figure 1-14 2-D sun path diagram

1.7 Main components of the photovoltaic systems:

The components of the photovoltaic system depend mainly on the application and the size of the system. There are two main types of the photovoltaic system, on grid system and off grid system (Roos, 2009).

1.7.1. On-grid photovoltaic system

In the on-grid system, the generated power is feed into the electrical network. It could have a storage system as an option. This system consists of, photovoltaic modules, inverter, protection devices, energy meter, foundation and supporter structures and wiring cables. In addition, battery bank and charge controller are added if a storage system is needed.

1.7.2. Off-grid photovoltaic system

In the off-grid system, the generated power is consumed and / or stored for local use. This system consists of photovoltaic modules, inverter, protection devices, foundation and supporter structures, wiring cables, and battery bank and charge controller. It is important to distinguish between the inverters used for on-grid system from the inverters used for the off-grid systems.

1.8 Research methodology

For photovoltaic systems, the STC values are (Air mass = 1.5, Irradiance 1000W/m^2, cell temperature 25^{o}C). Irradiance, by definition, is the rate at which radiant energy is incident on a surface per unit area of that surface (W/m^2). The efficiency of a photovoltaic system is measured by watt per meter square. Hence, either increase the total watts per meter square or minimize an area required for generating number of watts will improve PV efficiency.

Figure 1-15 Typical installation of a photovoltaic system (Rowena, 2018)

As shown previously, shading does drastically affect the output power from a photovoltaic system. Shading sources are varying in shape, location, obstacle, nearby objects, and photovoltaic rows in a system as shown in figure 1-16.

This thesis study will focus on shading from PV array rows, first row shadows cast on the second row in order to minimize the required area for a photovoltaic system. The methodology in this thesis will include conducting an experiment using small array of photovoltaic modules (nine modules, each of 3.5 watts) with varies distance between rows in order to explore the effect of shade on the optimum operating power from the module. Finally, the drop in module power were correlated with the distance between rows and linked to shadow formation time in the year to find the optimum distance between rows.

The process, which followed in this thesis, was:

1. Setup an experiment to study the effect of shade on the PV modules.
2. Calculate the minimum distance required between the PV rows to prevent shade casting from the PV rows in the field.
3. Finding the effect of shading during winter season on the output of the system and the land use.
4. Simulate an optimum distance between the PV rows to maximize the overall system efficiency.

2. CHAPTER 2: EXPERIMENTAL SET UP AND PROCEDURE

2.1 Introduction:

The experiment set up in this thesis will investigate different scenarios of the effect of symmetrical shading on PV cell and PV array output power. Firstly, the effect of shading on the photovoltaic modules during solar noon for different number and connection (series /parallel) of modules will be investigated.

Secondly, the required space between PV rows in the system will be studied. Since the efficiency of the PV, systems are measured by the amount of output power.

Thirdly, the effect of shading on the photovoltaic modules during solar noon for different connection between the modules and how does it affect the overall productivity per the available area., the theoretical minimum distance between rows will be calculated either from solar equations mentioned in the first chapter or from sun path diagrams.

Finally, the effect of the symmetrical shading produced from front rows on the array output power will be investigated. In this experiment, worst -case scenario, which is the minimum distance required between PV rows to minimize the effect of the shading on the whole system, will be simulated.