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Performance of Photovoltaic Module at Different Tilt Angles in Perlis, Northern Malaysia

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Abstract – This paper presents a calculation of the tilt angles and the solar irradiance on PV module in Perlis, Nortern Malaysia. A mathematical modeling is used to calculate the tilt angles and the solar irradiance, which depend on latitude and day number. The optimum tilt angle of PV module was determined by searching a yearly maximum total and average solar irradiance. The tilt angles of PV module in Perlis, Northern Malaysia are -17.16^0 to 29.74^0. For the state of Perlis, Northern Malaysia (has latitude 6.29^0 N) is recommended that the optimum tilt angle of the PV module from the horizontal be put equal to 6.84^0 (an angle of the latitude of the location +0.55^0). The best performance of PV module is reached when the tilt angle is 6.84^0.

***Keywords**: Solar irradiance; Optimum tilt angle; Performance of PV module*

Nomenclature

I_{tt} Total solar irradiance
I_{bt} Beam solar irradiance
I_{dt} Diffuse solar irradiance
I_{rt} Reflected solar irradiance
β_N Angle between the sun and the local horizontal directly beneath the sun
L Latitude of the site
δ Solar declination
$\sum$ Tilt angle of PV module
n Day number
θ Angle of incidence between a line drawn normal to the PV module
I_b Beam portion of the radiation reaching the earth's surface
A Apparent extraterrestrial flux
k Dimensionless factor called the optical depth
m Air mass ratio
ϕ_P Azimuth angle (measured relative to due south, with positive value in the southeast and negative value in the southwest)
ϕ_S Solar azimuth angle
H Hour angle
C Sky diffuse factor
ρ Reflectance
I Current generated by PV module
I_{sc} Short circuit current of PV module
I_0 Current generated by PV module relate to current density
V PV module voltage
R_s Series resistance of PV module
R_{sh} Shunt resistance of PV module
N_s Number of solar cells is connected in series
N_p Number of solar cells is connected in parallel

Subscript

Subscript M stands for 'Module' and subscript without M stand for a single solar cell

I. Introduction

The performance of a photovoltaic (PV) is highly influenced by its orientation and its tilt angle with the horizontal, due to the fact that both the orientation and tilt angle change the amount of solar radiation reaching the surface of the PV module, presented by [1]. The tilt angle of the fixed-structure PV module should be carefully evaluated for different places and periods of time to obtain the maximum overall output electrical energy. A mathematical model was used by [2] to estimate the global solar irradiance on the tilt PV surface, and to determine optimum tilt angles for PV module, the optimum tilt angle were determine by searching for the value of angle for which the global irradiance on the PV module surface was maximum. Empirical correlation for estimating the solar irradiance incident on horizontal surface have been proposed by [3], the result shown that in Jeddah (Saudi Arabia), the solar irradiance have to be tilted to face south with a tilt angle equals the latitude of the place in order to achieve the best performance all year round.

The optimum tilt angles of the PV module at any latitude, for any surface azimuth angles and on a day or a month of a year, have to be determined for design purpose. Definite value is rarely given by researchers

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for optimum tilt angles. The suggested optimum tilt by [4] is latitude angle $\pm 15^0$, (latitude angle + 15^0) $\pm 15^0$ by [5] and latitude angle $\pm 15^0$ by [6]. The optimal PV tilt angle and orientation depend on the local climate, the load consumption temporal profile and latitude.

Research result of [7] shown that using PV mounting structure of adjustable tilt angle can be obtained PV performance improvement of 5.6%. Improvement of PV panel is done by [8] by improving the PV panel model based on manufacture data, some results are given to approve that dark-saturation current and open-circuit voltage of the model both have the nonlinear relationships with the temperature and irradiance level. Maximum power point tracking (MPPT) techniques are used in photovoltaic systems to maximize solar array output power under variable conditions [9], objective of this research is to improve the performance of the photovoltaic systems.

This paper presents a calculation of the tilt angle and the solar irradiance on PV module in Perlis, Malaysia. Method of [10] is used to calculate the tilt angle and the solar irradiance, which depend on latitude and day number. The tilt angle and solar irradiance change every day in a year and analyzed. The monthly average solar irradiance are shown and analyzed in this paper.

II. Methodology

II.1. Latitude of Perlis

Base on Meteorological Station in Chuping Perlis, Perlis (6^0 29' N , 100^0 16' E) has about 795 square kilometers land area, 0.24% of the total land area of Malaysia, with a population about 204450 people [11], as shown in Fig. 1.

Fig. 1. Map of Perlis has latitude 6^0 29' N

II.2. Solar Irradiance

The electricity power generated by PV systems is directly related to the solar energy received by the PV module, while the PV module can be placed at any orientations and any tilt angles, but most local observatories only provide solar irradiance data on a horizontal surface. Thus, an estimation of the solar irradiance on a tilt surfaces is calculated by adding the beam, diffuse, and reflected solar irradiance components on the tilt surface together by [10], as in Fig. 2.

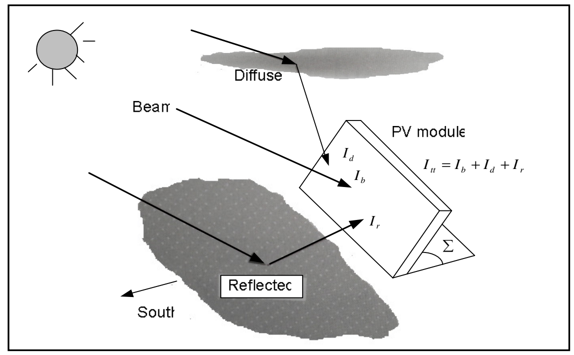

Fig. 2: Total solar irradiance on tilt surface of PV module

The total solar irradiance on tilt surface is given by:

$$I_{tt} = I_{bt} + I_{dt} + I_{rt} \quad (1)$$

where I_{tt} is the total solar irradiance on the tilt surface, W/m^2; I_{bt} is the total beam solar irradiance absorbed by the tilt surface, W/m^2; I_{dt} is the total diffuse solar irradiance absorbed by the tilt surface, W/m^2; and I_{rt} is the total reflected solar irradiance absorbed by the tilt surface, W/m^2.

II.3. Tilt Angle of a PV Module

An altitude angle or solar angle β_N is an angle between the sun and the local horizontal directly beneath the sun. The altitude angle of the sun at solar noon is shown in Fig. 3. From Fig. 3 can be written down the following relationship by inspection:

$$\beta_N = 90^0 - L + \delta \quad (2)$$

$$\Sigma = 90^0 - \beta_N \quad (3)$$

where L is the latitude of the site, δ is solar declination (the angle formed between the plane of the equator and a line drawn from the centre of the sun to the centre of the earth) and $\sum$ is tilt angle of PV module. According to [10], the solar declination δ is given by:

$$\delta = 23.45 \sin\left[\frac{360}{365}(n-81)\right] \qquad (4)$$

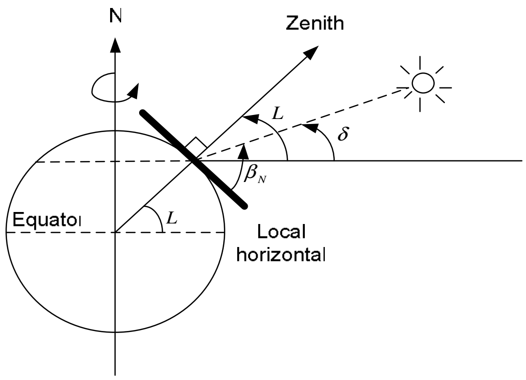

Fig. 3: The altitude angle of the sun at solar noon

where n is day number, with January 1 as day 1 and December 31 being day number 365.

II.4. Beam Solar Irradiance

The translation of direct-beam irradiance I_b (normal to the rays) into beam into beam irradiance striking a PV module face I_{bt} is a simple function of the angle of incidence θ between a line drawn normal to the PV module face and the incoming beam irradiance (Fig. 4). It is given by

$$I_{bt} = I_b \cos\theta \qquad (5)$$

where I_b is the beam portion of the radiation reaching the earth's surface (normal to the rays), is given by

$$I_b = Ae^{-km} \qquad (6)$$

where A is an "apparent" extraterrestrial flux, and k is a dimensionless factor called the optical depth, given by

$$A = 1160 + 75\sin\left[\frac{360}{365}(n-275)\right] \qquad (7)$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n-100)\right] \qquad (8)$$

The air mass ratio m is given by

$$m = \frac{1}{\sin\beta} \qquad (9)$$

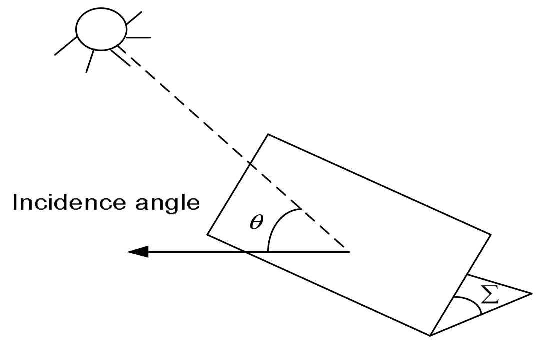

Fig. 4: The incidence angle θ between a normal to the PV module face and the incoming solar beam irradiance

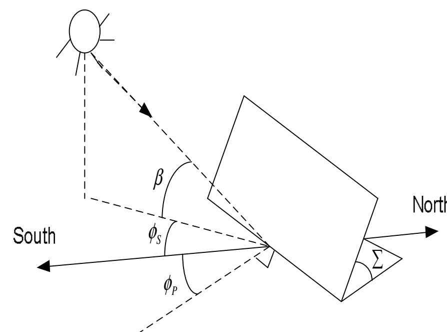

Fig. 5: Illustrating the PV azimuth angle ϕ_P and tilt angle $\sum$ along with the solar azimuth angle ϕ_S and altitude angle β. Azimuth angles are positive in the southeast direction and are negative in the southwest

The angle of incidence θ will be a function of the photovoltaic orientation and the altitude and azimuth angles of the sun at any particular time. Fig. 5 introduces these importance angles. The photovoltaic is tipped up at angle $\sum$ and faces in a direction described by its azimuth angle ϕ_P (measured relative to due south, with positive value in the southeast and negative value in the southwest). The incidence angle is given by

$$\cos\theta = \cos\beta\cos(\phi_S - \phi_P)\sin\Sigma + \sin\beta\cos\Sigma \qquad (10)$$

The solar azimuth angle ϕ_S is given by [10]

$$\sin\phi_S = \frac{\cos\delta \sin H}{\cos\beta} \qquad (11)$$

where H is hour angle (the number of degrees that the earth must rotate before the sun will be directly over local meridian or line of longitude), is given by [13]

$$H = \cos^{-1}(-\tan L \tan\delta) \qquad (12)$$

II.5. Diffuse Solar Irradiance

The simplest models of diffuse irradiation assume it arrives at a site with equal intensity from all direction; that is, the sky is considered to be isotropic. Obviously, on hazy or overcast days the sky is considerably brighter in the vicinity of the sun, and measurements show a similar phenomenon on clear days as well, but these complications are often ignored. The following expression for diffuse irradiance on the photovoltaic module

$$I_{dt} = CI_b\left(\frac{1+\cos\Sigma}{2}\right) \tag{13}$$

where C is a sky diffuse factor and a convenient approximation is a follows :

$$C = 0.095 + 0.04\sin\left[\frac{360}{365}(n-100)\right] \tag{14}$$

II.6. Reflected Solar Irradiance

The final component of irradiance striking a photovoltaic module results from radiation that is reflected by surfaces in front of the module. The simplest model assumes a large horizontal area in front of the module, with a reflectance ρ that is diffuse, and it bounce the reflected irradiance in equal intensity in all direction. The solar reflected irradiance is given by

$$I_{rt} = \rho\, I_b(\sin\beta + C)\left(\frac{1-\cos\Sigma}{2}\right) \tag{15}$$

II.7. Mathematical Modelling of PV Module Performance

The most popular photovoltaic module is a particular case of a series string of solar cells. In terrestrial application the PV standard modules are composed of a number solar cells connected series. The number is usually 33 to 36 but different associations are also available. The PV module characteristic is the result of the voltage scaling of the $I(V)$ characteristic of a single solar cell. Consider the $I(V)$ characteristic of a single solar [7], [10]:

$$I = I_L - I_0\left(e^{\frac{V+IR_s}{nV_T}} - 1\right) - I_{02}\left(e^{\frac{V+IR_s}{2V_T}} - 1\right) - \frac{V+IR_s}{R_{sh}} \tag{16}$$

Consider some simplifying assumptions, in particular that the shunt resistance, R_{sh}, of a solar cell is large and its effects can be neglected, and that the effects of the second diode are also negligible. So, assuming $I_{02} = 0$ and $R_{sh} = \infty$, equation (16) becomes

$$I = I_{sc} - I_0\left(e^{\frac{V+IR_s}{nV_T}} - 1\right) \tag{17}$$

where $I_{sc} = I_L$ has also been assumed.

The scaling rules of voltage, currents and resistances when a matrix of $N_s x N_p$ solar cells is considered are the following:

$$I_M = N_P I \tag{18}$$

$$I_{scM} = N_p I_{sc} \tag{19}$$

$$V_M = N_s V \tag{20}$$

$$V_{ocM} = N_s V_{oc} \tag{21}$$

where subscript M stands for 'Module' and subscript without M stand for a single solar cell. The scaling rule of the series resistance is the same as that of an $N_s x N_p$ association of resistors:

$$R_{sM} = \frac{N_s}{N_p} R_s \tag{22}$$

Substituting in equation (2),

$$\frac{I_M}{N_p} = \frac{I_{scM}}{N_p} - I_{01}(e^{\frac{\frac{V_M}{N_s} + \frac{I_M N_p}{N_p N_s}R_{sM}}{nV_T}} - 1) \tag{23}$$

$$I_M = I_{scM} - N_p I_{01}(e^{\frac{V_M + I_M R_{sM}}{nN_s V_T}} - 1) \tag{24}$$

Moreover, from equation (17) in open circuit, I_0 can be written as:

$$I_0 = \frac{I_{sc}}{(e^{\frac{V_{oc}}{nV_T}} - 1)} \tag{25}$$

Using now equation (4) and (6)

$$I_0 = \frac{I_{scM}}{N_p(e^{\frac{V_{ocM}}{nV_T N_s}} - 1)} \tag{26}$$

III. Results and Discussion

III.1. Tilt Angle of PV Module

The tilt angles of PV module were calculated using (2) to (4) for a year. The first, the solar declination δ was calculated for 365 days in a year and latitude of Perlis is $6^0\ 29^{'}$ N substituted in (2), finally the tilt angle $\sum$ could be calculated using (3). The tilt angles of PV module in Perlis, Northern Malaysia are shown in Fig. 6.

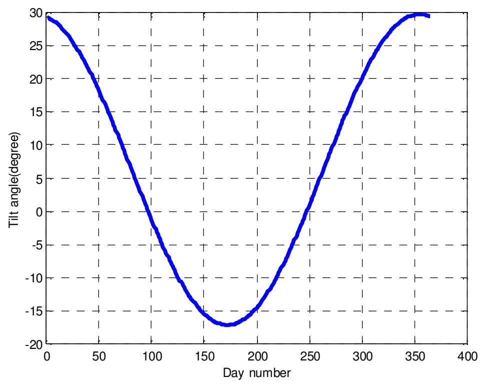

Fig. 6: The tilt angle of PV module in Perlis, Malaysia

The tilt angles have positive degree which indicate that the PV module is inclined to face south, negative degree indicate that it inclined to face north and zero degree indicate that it on horizontal surface [11].

Fig. 6 shows that the tilt angles can be divided to three parts, exactly positive, zero and negative. From the 1st January to the 6th April, the tilt angles of PV module in Perlis are positive (29.30^0 on the 1st January and 0.30^0 on the 6th April) which indicate that the PV module inclined to face south. For the 7th April and the 5th September, the tilt angles are 0^0 which indicate that the PV module on the horizontal surface. From the 8th April to the 4th September, the tilt angles are negative (-0.48^0 on the 8th April and -0.26^0 on the 4th September), maximum negative is -17.16^0 on the 22sd June which indicate that the PV module inclined to face north. From the 6th September to the 31st December, the tilt angles are positive (0.52^0 on the 6th September and 29.37^0 on the 31 December), maximum positive is 29.74^0 on the 21st December which indicate that the PV module inclined to face south.

III.2. Solar Irradiance on Tilt angles of PV Module

The effect of tilt angles of PV module on solar irradiance was calculated using (1) and (5) to (15) for a year. The solar irradiance on tilt angles of PV module are shown in Fig. 7.

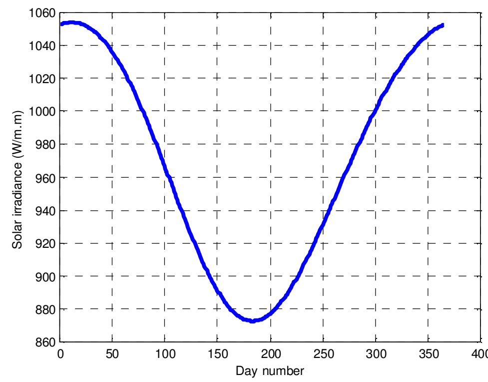

Fig. 7: Solar irradiance on tilt angles of PV module

Fig. 7 shows that the minimum, maximum and average solar irradiance are 872.52 W/m^2, 1053.9 W/m^2 and 967.97 W/m^2 which indicate that the sky in Perlis is clear and very high for a year and gives potential for PV power generation [12].

Fig. 8 shows 3-dimensional diagram of solar irradiance as function of both day number and tilt angle. When the tilt angles of PV module are positive (the 1st January to the 6th April and the 6th September to the 31st December), the solar irradiance around 929.60 W/m^2 to 1054 W/m^2 , the minimum and maximum solar irradiance happen on the 6th September and on the 6th to 17th January, respectively. When the tilt angle of PV module is zero (the 7th April and the 5th September), the solar irradiance is around 928.2 W/m^2. When the negative tilt angles of PV module (the 8th April to the 4th September), the minimum and maximum solar irradiance are 872.50 W/m^2 on the 2 July and 970 W/m^2 on 8th April, respectively. For one year, on 3 July and -16.76^0 of tilt angle the solar irradiance is minimum (872.50 W/m^2).

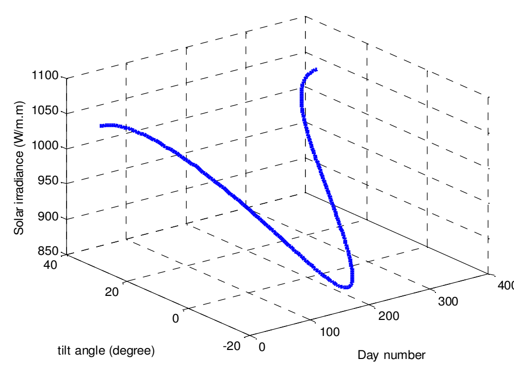

Fig. 8: 3-dimensional diagram of solar irradiance as function of both day number and tilt angle

The monthly minimum, maximum and average solar irradiance on tilt angles of PV module are shown in Fig.9.

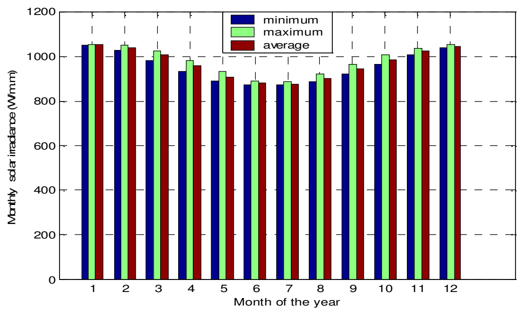

Fig. 9: Monthly minimum, maximum and average solar irradiance on tilt angles of PV module

Based on solar irradiance of a year, Perlis has a big solar irradiance potential, its average is 967.97 W/m^2. The monthly highest average solar irradiance is 1052.80 W/m^2 on January and its lowest is 876.70 W/m^2 on July. The minimum and maximum monthly solar irradiance are 872.50 W/m^2 on July and 1053.90 W/m^2 on January, respectively. These data show that the solar irradiance can be used for certain application, especially in PV power generation.

III.3. Optimum Tilt Angles of PV Module

Fig.10 indicates that the tilt angle has a very significant effect on the solar irradiance through the year. For the different tilt angle, the PV module has different solar irradiance through the year. For -17.16^0 of the PV module tilt angle, the minimum, maximum and average solar irradiance are 716.30 W/m^2, 929.90 W/m^2 and 844.50 W/m^2, respectively. For horizontal PV module, the minimum, maximum and average solar irradiance are 834.50 W/m^2, 995.70 W/m^2 and 920.50 W/m^2, respectively. For 6.84^0 of the PV module tilt angle, the minimum, maximum and average solar irradiance are 797.90 W/m^2, 1017 W/m^2 and 928.1 W/m^2, respectively. For 29.74^0 of the PV module tilt angle, the minimum, maximum and average solar irradiance are 596.70 W/m^2, 1054 W/m^2 and 858 W/m^2, respectively.

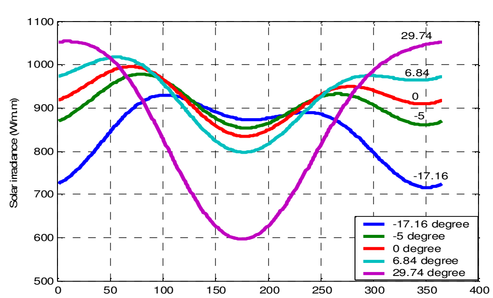

Fig. 10: Solar irradiance through the year on different tilt angle of PV module

Every tilt angle (-17.16^0 to 29.74^0) of PV module in Perlis was calculated to find the yearly total and average solar irradiance. The optimum tilt angle of PV module was determined by searching a yearly maximum total and average solar irradiance. This choice based on that under constant temperature if the solar irradiance increases, output power and efficiency of the PV module will increase [13]. Fig. 11 and 12 show the yearly total and average solar irradiance on different tilt angle of PV module.

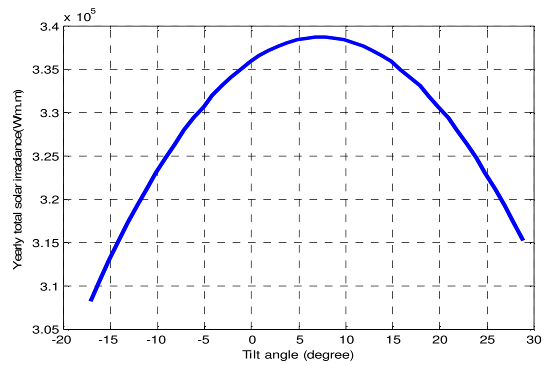

Fig. 11: Yearly total solar irradiance on different tilt angle of PV module

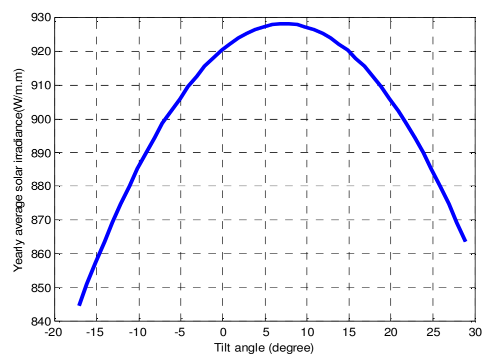

Fig. 12: Yearly average solar irradiance at different tilt angle of PV module

Fig. 11 and 12 show that the yearly maximum total and average solar irradiance are 338,700 W/m^2 and 928.1 W/m^2 on 6.84^0 of the PV module tilt angle. Under this solar irradiance and constant temperature, the PV module will produce the highest output power and efficiency.

III.4. Performance of PV Module at Different Tilt Angles

III.4.1. Solar Irradiance Effect

A 60 W, 21 V, BP SX 60 multi-crystalline silicon PV module was used in this paper. This PV module consists of 36 solar cells configured as 18 cell series strings. The complete data of the PV module is shown in Table 1.

Table 1. Electrical parameter of multi-crystal silicon PV module

	BP SX 60
Maximum power (P_{max})^2	60W
Voltage at P_{max} (V_{mp})	16.8V
Current at P_{max} (I_{mp})	3.56A
Guaranteed minimum P_{max}	55W
Short-circuit current (I_{sc})	3.87A
Open-circuit voltage (V_{oc})	21.0V

The performance of PV module under the yearly average solar irradiance at different tilt angle of PV module and constant temperature (25^{0}C) in Perlis simulated using PSpice. As representative of solar irradiance effect, the simulation was done for three different solar irradiance and tilt angles (844.5 W/m^2 and -17.16^0, 858 W/m^2 and 29.74^0, 928.1 W/m^2 and 6.84^0).

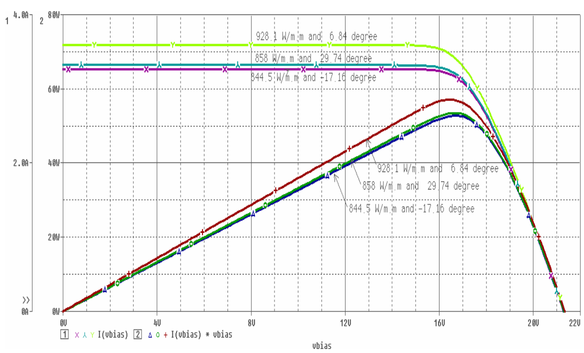

Fig. 13: Performance of PV module at different solar irradiance and tilt angle

Fig. 13 shows that the solar irradiance effect on the performance of PV module is much larger in the short circuit current than the open circuit voltage and gives significant effect on maximum power. The value of the short circuit current, maximum power and efficiency of each the solar irradiance can be seen in Table 2.

Table 2. Performance of PV module at different solar irradiance and tilt angle

Performance of PV module	**Solar irradiance And tilt angle**		
	844.5 W/m^2 and -17.16^0	858 W/m^2 and 29.74^0	928.1 W/m^2 and 6.84^0
Short circuit current (A)	3.27	3.32	3.59
Maximum power (W)	52.75	53.46	57.09
Efficiency (%)	87.92	89.10	95.15

Table 2 shows that under constant temperature, if the solar irradiance increase cause the electrical performance of PV module (short circuit current, maximum power, and efficiency) will increase. For solar irradiance of 928.1 W/m^2 and tilt angle of 6.84^0, the PV module has the best performance.

III.4.2. 3-Dimensional Diagram as Function of Both Solar Irradiance and Temperature

The Performance of PV module is depicted as function of both solar irradiance and temperature in 3-dimensional diagrams shown in Figure 14 to 15.

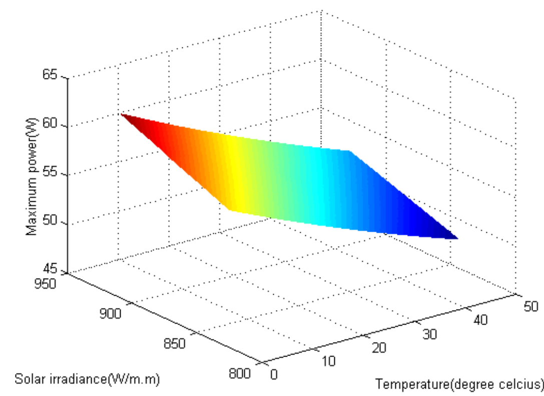

Fig. 14: PV module maximum power as function of both solar irradiance and temperature

Figure 14 shows that the maximum power of PV module as function of both solar irradiance and temperature. The figure shows that if the solar irradiance is constant and the temperature increase will cause the maximum power decrease, if the temperature constant and solar irradiance increase will cause the maximum power increase.

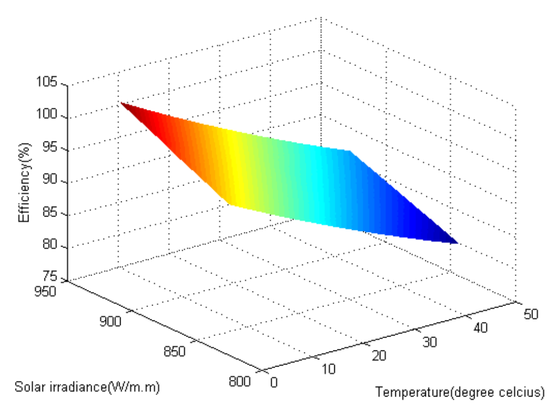

Fig. 15: PV module efficiency as function of both solar irradiance and temperature

Figure 15 shows that the efficiency of PV module as function of both solar irradiance and temperature. The figure shows that if the solar irradiance is constant and the temperature increase will cause the efficiency of PV module decrease, if the temperature constant and solar irradiance increase will cause the efficiency increase.

III.4.3 3-Dimensional Diagram as Function of Both Tilt Angle and Temperature

The Performance of PV module is depicted as function of both tilt angle and temperature in 3-dimensional diagrams shown in Figure 16 to 17. The tilt angles are the tilt angles in a year (-17.16^0 to 29.74^0).

Figure 16 shows that the maximum power of PV module as function of both tilt angle and temperature. The figure shows that if the tilt angle is constant and the temperature increase will cause the maximum power decrease. The maximum power of PV module in a year is reached when the optimal tilt angle is 6.84^0.

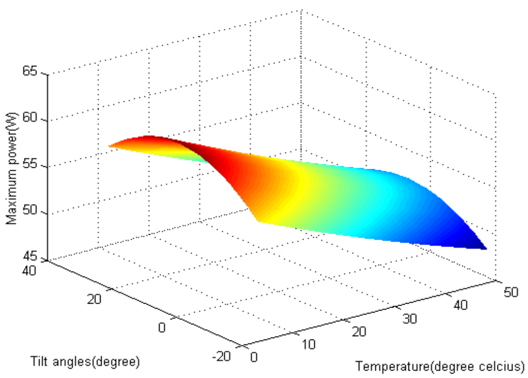

Fig. 16: PV module maximum power as function of both tilt angle and temperature

Figure 17 shows that the efficiency of PV module as function of both tilt angle and temperature. The figure shows that if the tilt angle is constant and the temperature increase will cause the efficiency decrease. The efficiency of PV module in a year is reached when the optimal tilt angle is 6.84^0.

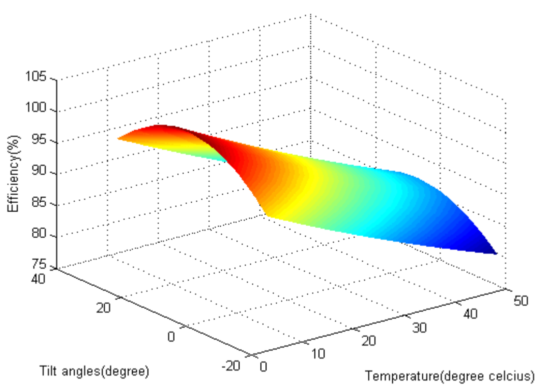

Fig. 17: PV module efficiency as function of both tilt angle and temperature

IV. Conclusion

The tilt angles of PV module effect on the solar irradiance that fall on its surface. The tilt angles of PV module in Perlis, Northern Malaysia are -17.16^0 to 29.74^0. The positive, zero and negative tilt angles indicate that the PV module is inclined to face south, on horizontal surface and north, respectively.

The optimum tilt angle of PV module was determined by searching a yearly maximum total and average solar irradiance. The yearly maximum total and average solar irradiance are 338,700 W/m^2 and 928.1 W/m^2 on 6.84^0 of the PV module tilt angle. Under this solar irradiance and constant temperature, the PV module will produce the highest output power and efficiency. For the state of Perlis, Northern Malaysia (has latitude 6.29^0 N) is recommended that the optimum tilt angle of the PV module from the horizontal be put equal to 6.84^0 (an angle of the latitude of the location $+0.55^0$).

In 3-dimensional diagram as function of both solar irradiance and temperature and also as function of both tilt angle and temperature, the best performance of PV module is reached when the tilt angle is 6.84^0.

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