Experimental Evaluation of the Performance of One-Axis Daily Tracking and Fixed PV Module in Baghdad, Iraq

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ABSTRACT:

An attempt was made to evaluate the PV performance of one-axis daily tracking and fixed system for Baghdad, Iraq. Two experimental simulations were conducted on a PV module for that purpose. Measurements included incident solar radiation, load voltage and load current. The first experiment was carried out for six months of winter half of year to simulate the one-axis daily tracking. The azimuth angle was due south while the tilt angle was being set to optimum according to each day of simulation. The second experiment was done at one day to simulate the PV module of fixed angles. It is found that there is a significant power gain of 29.6% for the tracking system in respect to the fixed one. The one-axis daily tracking was much more effective near winter solstice as compared to other months. The efficiency, fill factor for the one-axis and fixed module were 5.1%, 0.57, 4% and 0.52 respectively. Finally, it is concluded that power conditioning system is needed for load matching to improve PV performance.

Keywords: PV module, one-axis daily tracking, fixed system, experimental simulation, PV performance, power gain, fill factor.

التقييم التجريبي لأداء منظومة التتبع اليومي بمحور واحد والمنظومة الثابتة للوح شمسي في مدينة بغداد- العراق

حسين محمد تقي النجار – مدرس مساعد

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الخلاصة:

تم تقييم أداء لوح شمسي لمنظومتين .الاولى منظومة التتبع اليومي بمحور واحد والاخرى المنظومة الثابتة.أجريت المحاكاة التجريبية لهذا الغرض حيث تم قياس الاشعاع الشمسي الساقط وفولتية وتيار الحمل للحالتين. تمت التجربة الاولى لفترة ستة اشهر من الشتاء لمحاكاة منظومة التتبع اليومي بمحور واحد حيث كانت زاوية السمت للوح الشمسي باتجاه الجنوب بينما زاوية الميل هي المثلى لكل يوم من التجربة. أما التجربة الثانية فقد تمت ليوم واحد لمحاكاة المنظومة الثابتة للوح الشمسي. وجد بأن ربح القدرة 29.6% لمنظومة التتبع عن المنظومة الثابتة. كما أن منظومة التتبع كانت اكثر فعالية عند فترة الانقلاب الشتوي مقارنة مع الاشهر الاخرى. كانت الكفاءة وعامل الملأ لمنظومة التتبع اليومي و للمنظومة الثابتة 5.1% ، 0.57، 4% و 0.52 على التوالي. وأخيرا، يتطلب ربط منظومة تكييف القدرة لملائمة الحمل لغرض تحسين اداء اللوح الشمسي.

كلمات رئيسية: لوح شمسي،تتبع يومي بمحور واحد،منظومة ثابتة،محاكاة تجريبية،أداء اللوح الشمسي،ربح القدرة،عامل الملأ.

1. INTRODUCTION

PV arrays are increasingly being used for supplying electric power to individual and grid connected loads [Denholm and Margolis, 2007], [Meral and Dincer, 2011] and [Sidrach and Mora, 1998]. Since the input power to PV system varies in uncontrollable manner during each day, appropriate power conditioning system is, in most cases, required to match the operating characteristics of the PV generator with that of the load. Usually, power conditioning systems are designed using electronic equipment. Applications of such systems can be found in [Kim et al, 2009], [Hadi et al, 2003], [Tsang and Chan, 2013] and [Chiu et al, 2012]. In addition, to maximize the output power of a PV system, its orientation with respect to sun position need to be controlled. This process is called sun-tracking. Normally sun-tracking systems are evaluated by their power or irradiation gain in respect to fixed PV system. Different tracking systems have been studied and developed for various sites in the world.

[Neville, 1978] has shown theoretically that in mid latitude region, the power gain for one-axis and two-axis tracking can reach 36% and 41% respectively. The actual gains are depending on the local meteorological conditions.

In Jordan, [Abdallah, 2004] has studied experimentally different types of tracking systems. For one-axis, it is found that the power gain is 15.7-37.5% for a particular day in May. Using two-axis tracking, [Abu-Khader et al, 2008] have found by experimental investigation that the gain is 30-45% for two particular days in May and October.

In Syria, [Al-Mohamad, 2004] showed that one-axis azimuth tracking panel can produce a daily gain of 20%.

[Senpinar and Cebeci, 2012] used two-axis tracking experimental system with storage battery and inverter to find a daily gain in Elazig city, Turkey. The gain was 13.25% for a particular day in October. Also, in Turkey, at Mugla university, using two 7.9 KW grid-connected PV systems, [Eke and Senturk, 2012] calculated the annual gain for two-axis tracking and found to be 30.79%.

In Tunisia, [Maatallah et al, 2011] investigated theoretically the monthly gains for single and double axis PV tracking panels in Monastir city. They found that the maximum gains for single axis tracking were 15.44% and 10.34% at winter and summer solstices respectively. Whereas, for double axis tracking, the maximum gains were 30% and 44% respectively.

[Chang, 2009] studied theoretically the electric energy from PV module at different azimuth and tilt angles in Taiwan. It is found that the yearly gain was 18.7% for one-axis tracking.[Huang et al, 2011], in Taipei, Taiwan, utilized one-axis 3-position sun-tracker for PV power generation to lighting system. The annual power gain was found to be 23.6%. They showed that, in areas of high solar energy resource, the one axis 3-position tracking can perform very close to two-axis tracking at lower cost with annual gain of 37.5%.

In Spain, based on irradiation data for 52 main cities, [Cruz-Peragón et al, 2011] made analyses for PV solar systems using theoretical modeling. The results gave an overall annual energy gain of 30-35% for two-axis tracking.

In the USA, [Lubitz, 2011] utilized hourly typical meteorological data to simulate the irradiation on solar panels for different 217 sites. The overall annual irradiation gain for one-axis azimuth and two-axis tracking was 29 and 34% respectively.

The present study aimed to evaluate the PV performance: output power, efficiency and fill factor in Baghdad city, Iraq, using one-axis daily tracking and fixed systems. Average power gain is also to be obtained. For that purpose, experimental simulations on a PV module are carried out for six months of winter half of year. No previous published paper was found concerning performance comparison of tracking and fixed PV module for Iraq.

2. PV MODULE CHARACTERISTICS
[Duffie and Beckman, 2006] and [Patel, 2006]

A PV cell is a semiconductor p-n junction diode that converts part of the incident solar radiation directly into dc current by photoelectric effect. PV modules are available with many cells connected in series and parallel to provide convenient currents and voltages. Practically, an array of identical PV modules (PV system) is arranged in series and parallel to obtain the desired current and voltage for the power system to which it is connected.

The design of power systems using PV modules as generator must be based on the electrical characteristics ,that is , the voltage – current relationships of the PV system under various levels of incident solar radiation,G_T and module's temperature,T_c .

The current-voltage and the output power characteristics of a typical PV module are shown in **Fig.1**. It is simply all of possible operating points for a PV module at given incident solar radiation and module temperature.

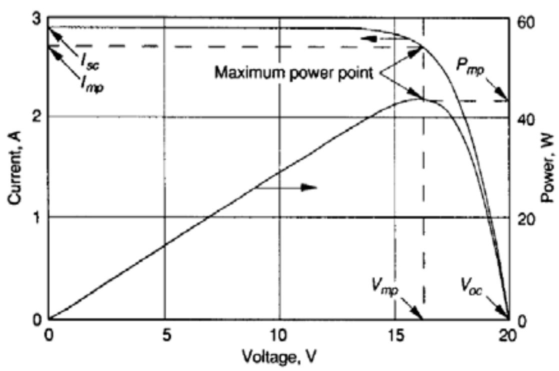

Fig.1: Typical I-V and P-V curves for a PV module.

Practically, PV modules operate at a point on the I-V curve that matches the I-V characteristics of the load. The output power of a module is:

$$P = V\ I \tag{1}$$

In certain cases, direct coupling of PV system with the load via storage system can be used. Otherwise, decoupling using appropriate power conditioning system may be needed to operate at maximum power point (mp), where the voltage, current and output power are V_{mp} ,I_{mp} and P_{mp} respectively. For ac power system, inverters of desired frequency will be required.

A commonly used parameter that characterizes a PV module is the fill factor FF, which relates the maximum output power P_{max} to the open-circuit voltage V_{oc} and the short-circuit current I_{sc} as

$$FF = \frac{P_{max}}{V_{oc}\ I_{sc}} \tag{2}$$

It is found that the fill factor gives a measure of the efficiency of PV module [Amori and Al-Najjar, 2012].

The voltage V_{oc} is temperature dependent and it decreases with module temperature; while the current I_{sc} increses slightly and it is normally ignored.

The I_{sc} is directly proportional to incident radiation; while voltage variation is logarithmic and usually ignored at high radiation levels.

The efficiency of a PV module is:

$$\eta = \frac{P}{A\ G_T} \tag{3}$$

where A is the surface area of PV module.

The major factor affecting the output power of a PV system is the absorbed energy by PV surface which is a function of PV material characteristics, the incident solar radiation and its angles of incidence on the PV surface.

The incident solar radiation on a PV surface consists of three components: beam, diffuse and ground reflected. Consequently, the absorbed radiation on the PV surface has three corresponding components and angles of incidence. The beam component is the radiation received without scattering by the atmosphere while the diffuse component is that received after scattering (sky radiation). The third component is the reflected radiation from ground and surroundings.

Different correlations are available to calculate these radiation components and their angles of incidence according to local meteorological conditions.

For PV modules that are usually facing south, as in Iraq, the incidence angle θ of beam radiation is found by:

$$cos\theta = \cos(\varphi - \beta)\ cos\delta\ cos\omega + sin(\varphi - \beta)\ sin\delta \tag{4}$$

where $\theta, \varphi, \beta, \delta$ and ω are the incidence angle of beam radiation, latitude of location, tilt angle of

PV module, declination angle and hour angle respectively.

The absorbed beam radiation by PV surface is proportional to the cosine of its incidence angle. For clear sky condition, a major part of the total absorbed radiation is due to the beam component. For such cases, the output power of PV systems is approximately proportional to $cos\theta$.

3. TRACKING SYSTEMS FOR PV MODULES [Kalogirou, 2009] and [Duffie and Beckman, 2006]

As discussed above, PV modules are most efficient when oriented perpendicular to the sun's rays, that is, $\theta = 0$. The orientation of a PV module can be specified by two angles: the tilt angle β and the azimuth angle γ, see **Fig.2**. These two angles can be changed during each day with the sun position such that to minimize the angle of incidence θ of the beam radiation on PV surface and thus maximize the incident beam radiation. This process is called sun tracking.

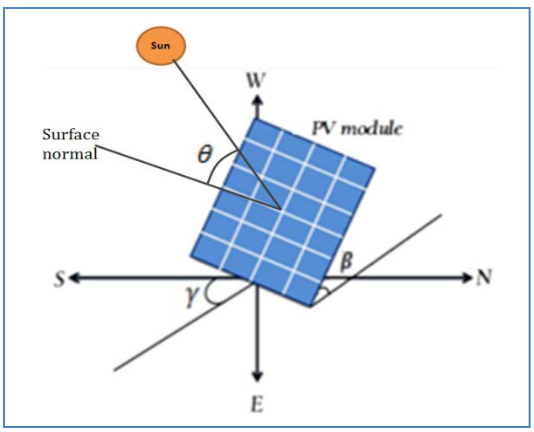

Fig.2: Tilt, azimuth and incidence angles for PV module

For fixed PV module at above the Tropic of Cancer, as for Iraq, both angles are kept unchanged. The azimuth angle γ is facing south and the tilt angle β is set at the latitude of the location for maximum annual insolation, thus:

$$\gamma = 0 \text{ and } \beta = \varphi . \quad (5)$$

This will be simulated experimentally in this paper. The incidence angle, from eq. (4), will be:

$$cos\theta = cos\delta \, cos\omega \quad (6)$$

Tracking systems are classified according to their axes of rotation. Rotation can be about one axis. Practically, there are four types of one-axis tracking namely: horizontal east-west, horizontal north-south, vertical and parallel to earth's axis. Each has its own scheme for adjustment of angles for the PV surface.

In this paper, the one-axis tracking of horizontal east-west axis rotation is applied experimentally.

In this scheme of tracking; at above the Tropic Cancer, the two angles are:

$$\gamma = 0 \quad (7)$$

and

$$\beta = \varphi - \delta \quad (8)$$

The declination angle is given by:

$$\delta = 23.45° \sin\left(\frac{360}{365}(n + 284)\right) \quad (9)$$

where, n is nth day of the year.

The tilt angle is adjusted on daily basis. Thus, this scheme is called one-axis daily tracking. The incidence angle, from eq. (4), is:

$$cos\theta = cos^2\delta \, cos\omega + sin^2\delta \quad (10)$$

Thus, beam radiation is normal to the PV surface at solar noon each day.

For rotation about two axes, both angle β and γ of the PV system are adjusted continuously such that the PV surface is always oriented perpendicular to the beam radiation.

For any tracking system, design and implementation are needed to produce the required control actions of angles for the PV system. The cost of tracking system should be taking into account in calculating energy yields as compared to fixed system [Cruz-Peragón et al, 2011].

4. EXPERIMENTAL SETUP

A PV module of type PQ10 with surface area 0.209m^2 is used for the experimental simulations.

This module is available at the energy engineering department. However, its power characteristics are unknown.

A test is carried out on the PV module to determine its characteristics. A variable-load method is applied using the circuit of **Fig.3** where the voltage and current of the load are measured at different values of load resistance under constant solar radiation G_T and ambient temperature, T_a.

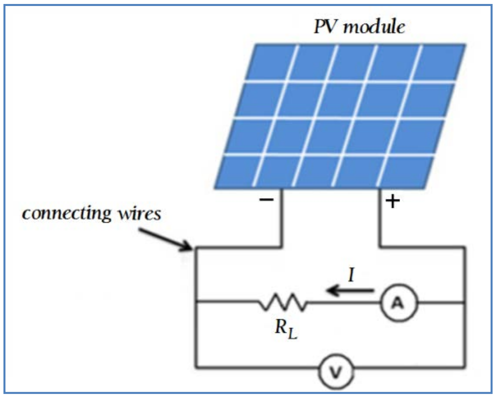

Fig.3: Circuit diagram for the experiments

The results are shown in **Fig.4**, **Fig.5** and **Table 1** for G_T=1178W/m^2 and T_a=14.5 °C.

Fig.4 shows the obtained I-V curve for the PQ10 PV module which indicates the open-circuit voltage V_{oc} , the short circuit current I_{sc} and the maximum power point (mp). The P-V curve is given in **Fig.5**, while **Table 1** summarizes the characteristics of the PQ10 PV module.

Two sets of experiments are to be conducted on the PQ10 PV module to evaluate its performance for the one-axis daily tracking system and the fixed system; one set for each system.

The experiments are carried out in clear sky days at the solar energy laboratory of energy engineering department at the college of engineering, Baghdad/Al-Jadria. The circuit diagram of **Fig.3** is used with resistive load of R_L=5Ω, that is direct coupling without storage system. The experimental measurements included incident solar radiation G_T, load voltage V, load current I, open-circuit voltage V_{oc} and short-circuit current I_{sc}. Adjustment of PV angles, during the experiments, is done manually.

The first set of experiments simulates the one-axis daily tracking of the PQ10 PV module. It is conducted for a period of six months: from 13 October 2010 to 13 April 2011. In this experiment, the azimuth angle of the module γ is fixed at zero, eq.(7), that is facing south. While the tilt angle β for each day of measurements is set according to eq.(8) where $\varphi = 33°$ for Baghdad. The daily value of tilt angle is shown in **Fig.6**. Measurements are carried out three times during a month around solar noon. The power obtained is the average output power of the PV module for the day.

The second set of experiments is to simulate the fixed PQ10 PV module; that is fixed in both angles. The azimuth angle of the module $\gamma = 0$ and its tilt angle $\beta = \varphi = 33°$ according to eq.(5). The experiment carried out for one day at 9 April 2011; from 8:00 am to 5:30 pm. Measurements are taken at every half-hour. The power obtained is the instantaneous output power of the PV module. The date of the experiment is chosen such that the corresponding tilt angle is close to the annual value, see **Fig.6**. In this case, moderate results will be obtained when compared with tracking system.

5. RESULTS AND DISCUSSION

The measurements results and calculated power of experiment no.1 (one-axis daily tracking) is shown in **Table 2**. Also, the average power and fill factor are given.

The voltage and current of the PQ10 PV module are plotted versus the number of the day as shown in **Fig.7**. As can be noticed, there are some fluctuations of 1.2V and 0.25A during the total period of experiment. This is due to changes in the atmospheric conditions where the incidence angle is kept near zero, as measurements are taken around solar noon of each day.

The output power and the incident solar radiation are plotted as shown in **Fig.8**. The change in power is 2.81 W due to variations in module temperature and solar radiation. The average output power for the total period of experiment is 12.90 W and the average solar radiation is 1032 W/m^2.

For the whole period of six months, the minimum efficiency was 5.1% and the average fill factor 0.57. The low values of efficiency and fill factor are due to that the maximum power point changes with module temperature and solar radiation. Thus, storage and/or power conditioning systems are required to keep the operation of PV system near the maximum power point of the IV characteristics.

For experiment no.2, which simulates the fixed PV module, the results and calculated power are shown in **Table 3**. Also, the average power and fill factor are given.

The voltage and current are plotted versus the day time as shown in **Fig.9**. Because of large changes in the incident angle on fixed PV surface from morning to evening, the changes in voltage and current are consequently large. The shape of the voltage and current graphs are like a sinusoidal function. The maximum values are 8.1V and 1.47A respectively at solar noon.

The power output and the incident solar radiation for the fixed PQ10 PV module are shown in **Fig.10**. They have the same shape of sinusoidal function also with maximum values of 11.76W and 866W/m^2 respectively. During the effective hours of the day, 9:00am-3:00pm, the average values of output power and solar radiation are 9.95W and 725W/m^2 respectively. Thus, the ratio of average to maximum power is 84%. The power decreases away from solar noon due to increase in the incidence angle.

The minimum efficiency during the effective hours of the day is found to be 4% and the fill factor is 0.52. Again, it is noticed that low efficiency and fill factor is due to PV operation far from maximum power point of the I-V curve. This can be improved using storage and/or power conditioning systems.

From the experimental simulations no.1 and no.2, the performance of PQ10 PV module can be evaluated as follows. The ratio of average power of the one-axis daily tracking to that of the fixed module is 1.296(12.9W/9.95W). That is, there is 29.6% gain in output power. This figure corresponds to the time period of the experiments in the year.

Also, it can be noticed from **Table 2** that the power output for the one-axis tracking in the winter period from 29 December to 28 February is more higher than other months as compared to that of fixed module. This is due to better angle of incidence during the above period where declination is maximum. The same would be applied for summer period of June and July.

The low efficiency and fill factor in both cases are due to great mismatch between PV and load characteristics. However, the one-axis tracking has somewhat higher values.

Finally, **Table 4** summarizes the performance characteristics obtained of the two experimental simulations for the PV module.

6. CONCLUSION

In this work, experimental simulations on a PV module were carried out to evaluate the PV performance characteristics of one-axis daily tracking and fixed system, see **Table 4**. No previous published work was found concerning the performance comparison of tracking and fixed PV module for Iraq. On the basis of the present work, the following conclusions have been found:

- There is a significant power gain, for the half-year period, of 29.6% for the tracking system relative to the fixed PV system.
- Since the obtained power gain is higher than the cost of tracking system (15-20% [Cruz-Peragón et al, 2011]), better profitability can be achieved in Iraq with PV tracking.
- The one-axis daily tracking is much more effective near winter and summer solstices as compared to other months of the year.
- Power conditioning system is required for load matching to improve the output power, efficiency and fill factor of PV module.

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LIST OF SYMBOLS

A: surface area of PV module (m^2).

FF: fill factor of PV module.

G_T: incident solar radiation on the surface of PV module (W/m^2).

I: load current of PV module (A).

I_{mp}: load current at maximum power point (A).

I_{sc}: short-circuit current (A).

mp: maximum power point on the I-V curve.

n: nth day of the year (n=1 for 1st January).

P: output power of PV module (W).

P_{max}: maximum output power (W).

P_{mp}: output power at maximum power point (W).

PV: photovoltaic.

R_L: load resistance (Ω).

T_a: ambient temperature (°C).

T_c: module temperature (°C).

V: load voltage of PV module (V).

V_{oc}: open-circuit voltage (V).

V_{mp}: load voltage at maximum power point (V).

β: tilt angle: the angle between the plane of PV surface and the horizontal; $-90° \leq \beta \leq 90°$.

γ: azimuth angle: the deviation of the projection on a horizontal plane of the normal to PV surface from the solar noon; $-180° \leq \gamma \leq 180°$.

δ: declination angle: the angular position of the sun at solar noon with respect to the plane of the equator; $-23.45° \leq \delta \leq 23.45°$.

η: efficiency of PV module.

θ: angle of incidence: the angle between the beam radiation on PV surface and the normal to that surface.

φ: latitude: the angular location north or south of the equator; $-90° \leq \varphi \leq 90°$.

ω: hour angle: the angular displacement of the sun east or west of the solar noon due to earth rotation at 15° per hour.

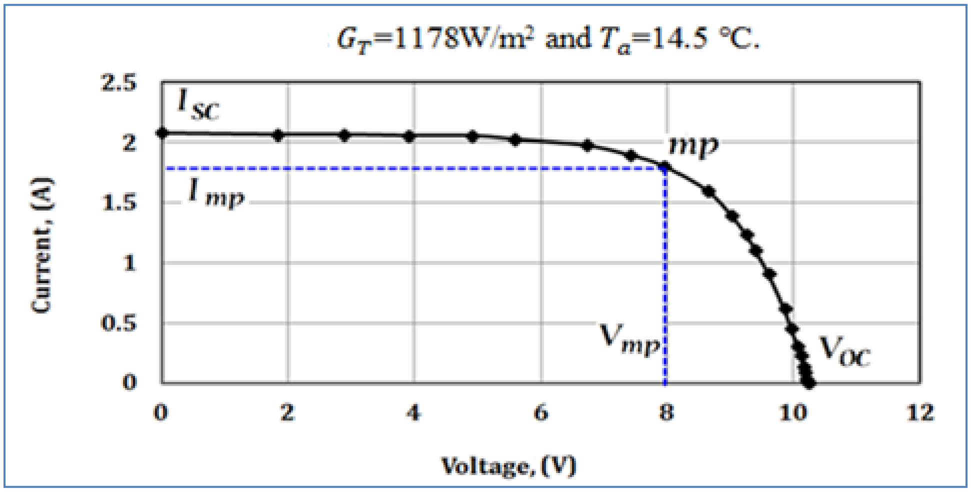

Fig.4: I-V curve of PQ10 PV module.

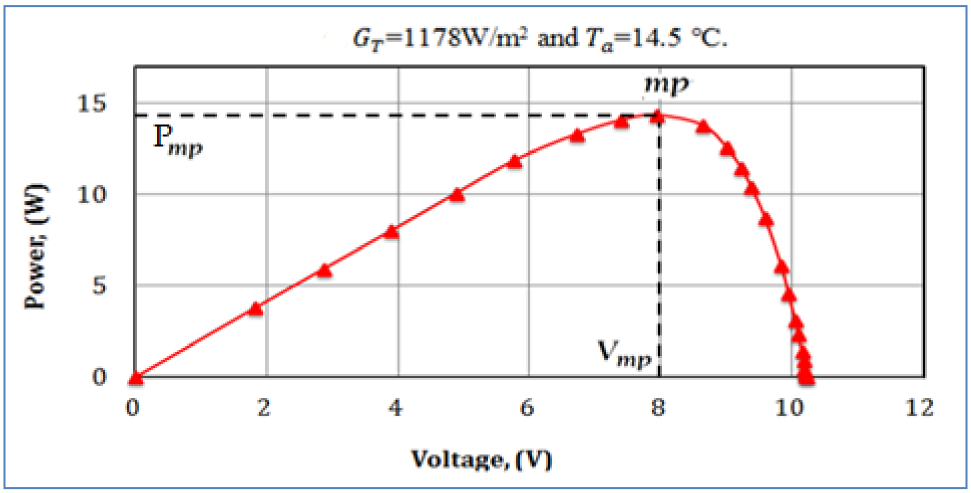

Fig.5: P-V curve of PQ10 PV module.

Table 1:PQ10 PV module characteristics at G_T=1178W/m^2 and T_a=14.5 °C.

Power at maximum power point, P_{mp}	14.48 W
Current at maximum power point, I_{mp}	1.81 A
Voltage at maximum power point, V_{mp}	8.0 V
Short-circuit current, I_{sc}	2.08 A
Open-circuit voltage, V_{oc}	10.23 V
Resistive load at maximum power point, R_L	4.42 Ω
Fill factor, FF	0.68
Surface area, A	0.209 m^2

Table 2: Data of Experiment no.1: one-axis daily tracking of PQ10 module

Date	Incident solar radiation (W/m^2)	Load voltage (V)	Load current (A)	Daily output power (W)
13 Oct. 2010	1139	8.5	1.53	13.01
20 Oct. 2010	1096	8.5	1.37	11.65
27 Oct. 2010	1118	8.6	1.38	11.87
10 Nov. 2010	1025	8.4	1.40	11.76
17 Nov. 2010	1080	8.3	1.51	12.53
24 Nov. 2010	850	8.4	1.43	12.01
01 Dec. 2010	1173	9.1	1.44	13.10
22 Dec. 2010	680	8.6	1.40	12.04
29 Dec. 2010	821	9.3	1.44	13.39
05 Jan. 2011	952	8.6	1.60	13.76
12 Jan. 2011	1085	9.3	1.51	14.04
10 Feb. 2011	1153	8.8	1.63	14.34
21 Feb. 2011	1115	9.3	1.45	13.49
28 Feb. 2011	1133	8.9	1.52	13.53
06 Mar. 2011	1095	8.7	1.47	12.79
14 Mar. 2011	1173	9.0	1.59	14.31
29 Mar. 2011	1115	8.7	1.49	12.96
13 Apr. 2011	765	8.1	1.42	11.53
Average of output power = 12.90W, Fill Factor = 0.57				

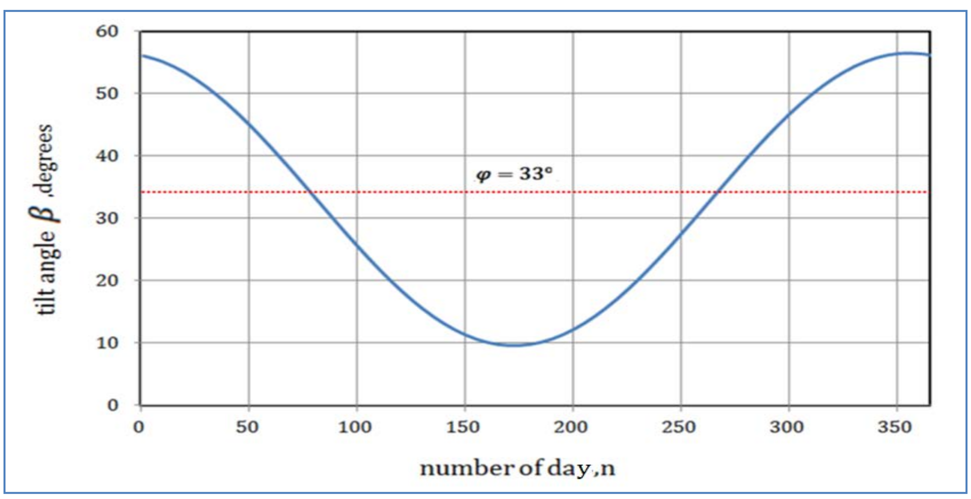

Fig.6: Daily value of tilt angle for one-axis daily tracking in Baghdad.

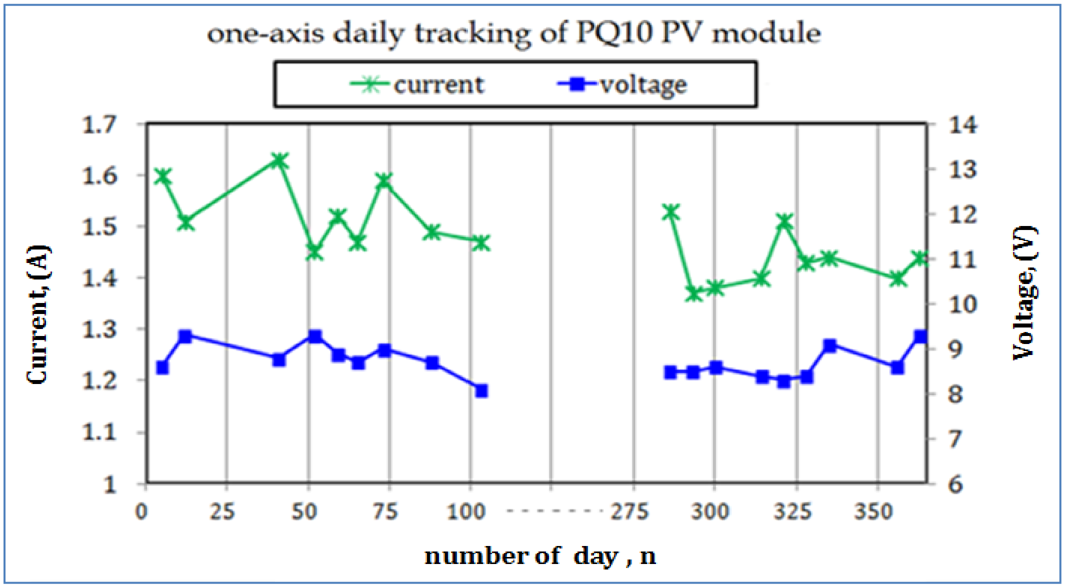

Fig.7: Load current and voltage of Experiment no.1

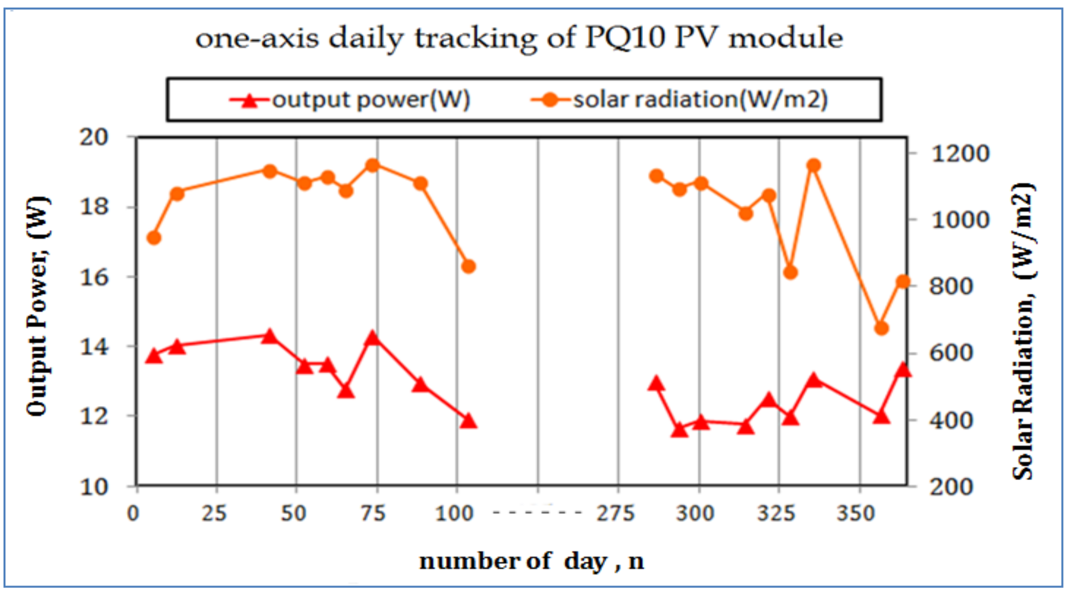

Fig.8: Output power and solar radiation for Experiment no.1

Table 3: Data of Experiment no.2: fixed PQ10 PV module.

Time (hr)	Incident solar radiation (W/m^2)	Load voltage (V)	Load current (A)	Instantaneous output power (W)
08:00 am	318	3.0	0.55	1.65
08:30 am	444	4.8	0.86	4.13
09:00 am	549	6.0	1.09	6.54
09:30 am	625	6.9	1.25	8.63
10:00 am	716	7.6	1.38	10.49
10:30 am	766	7.8	1.41	11.00
11:00 am	833	8.1	1.43	11.58
11:30 am	855	8.1	1.45	11.75
12:00 pm	866	8.0	1.47	11.76
12:30 pm	859	8.0	1.46	11.68
01:00 pm	808	7.9	1.43	11.30
01:30 pm	758	7.7	1.40	10.78
02:00 pm	689	7.4	1.33	9.84
02:30 pm	597	6.8	1.22	8.30
03:00 pm	504	5.6	1.01	5.66
03:30 pm	395	4.3	0.77	3.31
04:00 pm	295	3.2	0.57	1.82
04:30 pm	185	1.9	0.35	0.67
05:00 pm	115	0.9	0.16	0.14
05:30 pm	23	0.2	0.05	0.01
Average of output power = 9.95W, Fill Factor = 0.52				

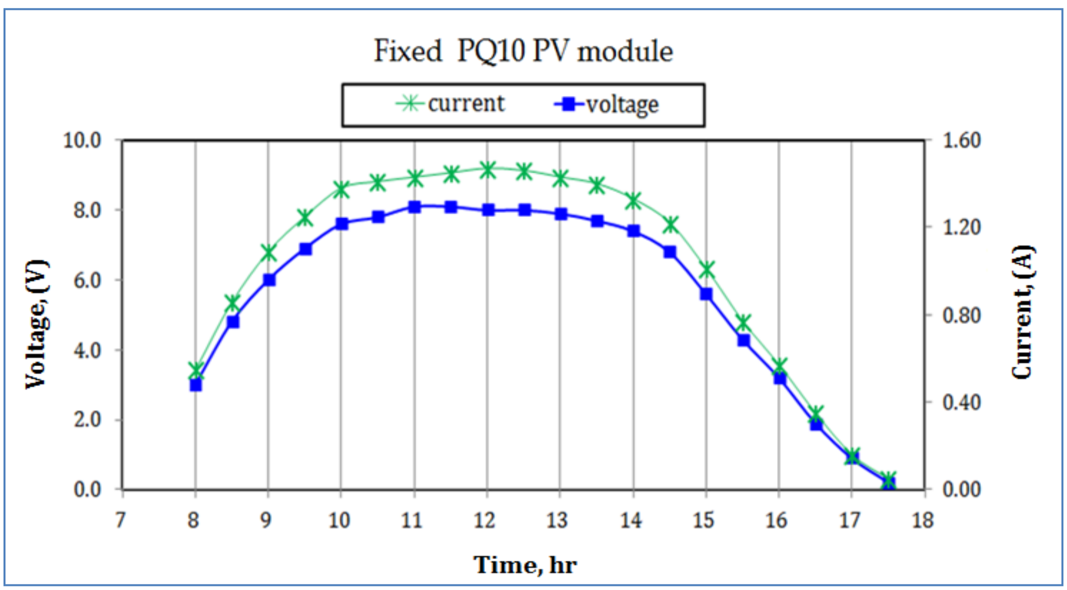

Fig.9: Load current and voltage of Experiment no.2

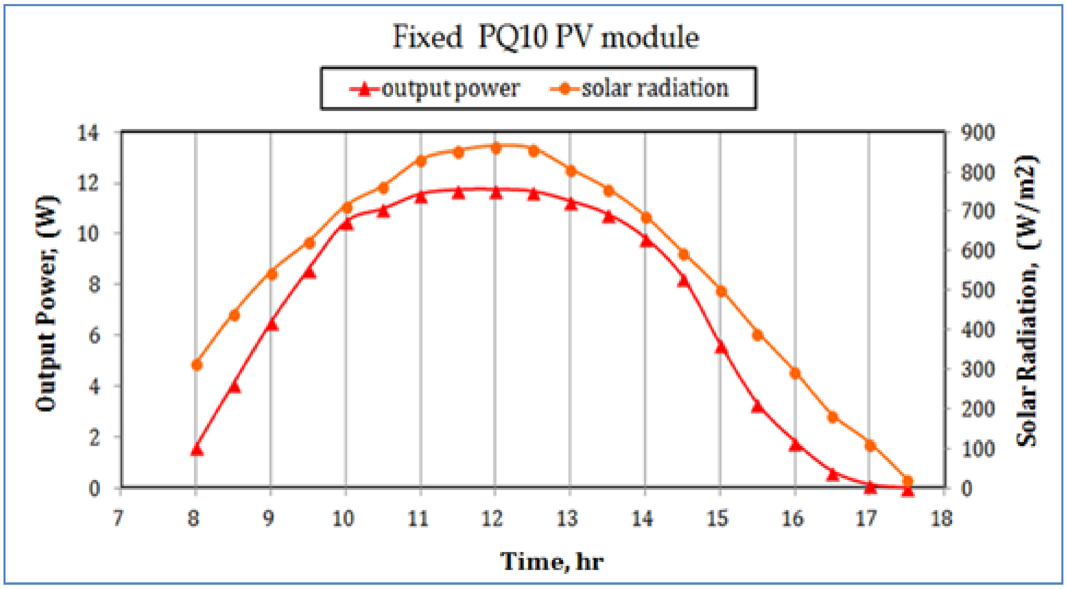

Fig.10: Output power and solar radiation of Experiment no.2

Table 4: Comparison of PV performance.

Performance characteristics	PQ10 PV module	
	One-axis daily tracking module	Fixed module
Average of output power	12.90 W	9.95 W
Minimum efficiency	5.1 %	4 %
Fill factor	0.57	0.52