Kuwait J. Sci. Eng. **37** (1A) pp. 99-109, 2010

Investigation of a photo-voltaic system with variable solar modules inclination angles

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ABSTRACT

This paper describes the design and investigation of a photo-voltaic system with variable solar modules inclination angles. The current-voltage (I-V) characteristics of a single crystal module are investigated under natural conditions. The PV system contains 180 modules of area of 0.37-0.39m^2. The inclination angle of each module with the horizontal plane was 23^o, 34^o and 45^o. The latitude of the PV station's location is 34^o N. Investigations were performed on clear and variable cloud days. An increase of 12-19% in the produced electrical energy is observed with an increase in the inclination angle in the winter period i.e. February 2009. The efficiency of the modules was in the range of 11%-12% at the change of inclination angles. A simple PV module's support was designed in order to easily change the modules inclination angle. The total numbers of the supports were 34 and on each support 5 to 6 modules were installed. Approximately one and one half hour was necessary to change the inclination angle of all the modules seasonally.

Keywords: Photovoltaic power system, module, variable inclination angle, current-voltage characteristics, efficiency.

INTRODUCTION

Energy is a vital factor in the industrial and socio-economic development of a country. However, there is also a direct link between the growth in energy and environmental pollution and it is one of the biggest challenges confronting modern civilization. In this context, the utilization of solar energy, which is environment-friendly, is very important for sustainable development.

At present, photo-voltaic (PV) technology is used for the conversion of solar energy into electrical energy in many countries around the world (Green 2004, Twidell & Weir 1986, Boyle 1996, Wrixonet *et al.,* 1993, Markvart 2000, Sharma and Saini, 2003, Zaidi *et al.,* 2000, Akhter 2002, Karimov *et al.,* 2005). The photovoltaic industry is growing 30% annually and has quadrupled in five years. Solar electricity finds applications in a number of systems, for instance, rural electrification, water pumping, satellite communications, grid-connected applications and corrosion protection such as cathodic protection for bridges, pipeline protection, well-head protection, lock gate protection and steel structure protection, etc.

The efficiency of a PV system depends on several factors such as; a) natural climatic conditions of the place where the system is to be used; b) optimal matching of the system with the load; c) appropriate spatial placement of the modules, i.e., placing the modules at an optimal inclination angle to the horizontal plane, and d) the availability of a concentrator (reflector) and or solar-tracking mechanism in the system (Karimov *et al.,* 2002) (Fig. 1). The majority of the PV systems used universally are the fixed solar modules; however, the tracking systems are also used for low-power applications (Green, 2004, Twidell & Weir, 1986, Boyle, 1996, Wrixonet *et al*., 1993, Markvart, 2000). Tracking solar modules collect higher solar energy than those of the fixed solar modules (Karimov *et al.,* 2002).

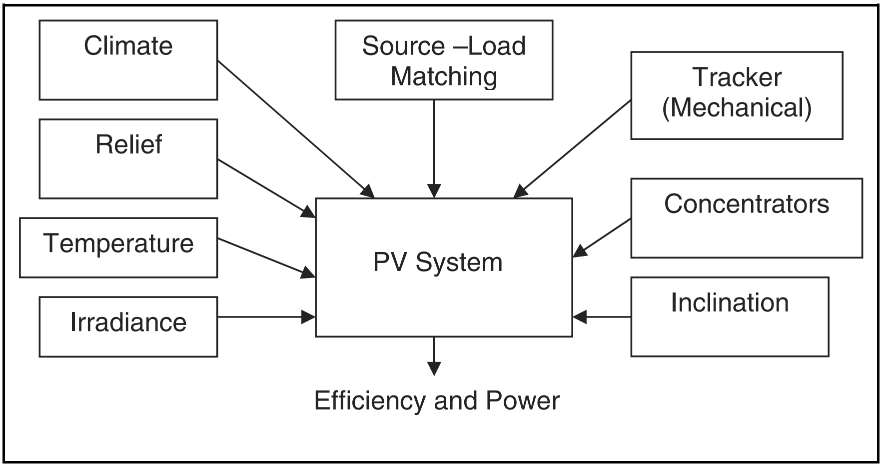


Figure 1: Dependence of PV system's efficiency on different factors.

At the same time, the tracking systems are less reliable and more expensive because of the presence of electric (Dadamukhamedov *et al*., 1998, Poulek & Libra, 1998) or mechanical motors (Markvart, 2000) and moving parts. Frequent maintenance requirements for these systems are problematic, especially in remote-area applications. Solar tracking systems have additional modules for sensing or driving purposes, other than the main modules, that feed a DC motor which is used to rotate the main modules (Kelly, 1984, Zerlant, 1989, Haywood, 2001). This obviously increases the cost of the system. In addition, the sensing or driving solar modules in these systems are installed perpendicular to the main modules; this increases the wind resistance of the system and thus makes it less reliable because the wind may interfere with solar tracking by the DC motor and unpredictably change the position of the modules. In the majority of the tracking photo-voltaic systems, there is no mechanism to fix the inclination angle of the modules in different seasons of a year. Fixed photo-voltaic systems, with aligned modules, are reliable but they have lower efficiency compared with those of the tracking systems.

To increase the output energy of photo-voltaic systems, different concentrators such as Fresnel lenses, parabolic reflectors, Winston reflectors and plane-side symmetrical reflectors are used in practice (Green, 2004, Twidell & Weir, 1986, Markvart, 2000). Most concentrators can only utilize direct solar radiation and work efficiently in tracking systems. Some of the unconventional designs of the concentrators, such as the Winston' type or fluorescent (or luminescent) concentrators (Twidell & Weir, 1986) allow some diffuse radiation as well as the direct radiation to be concentrated, and can work as static concentrators. The fluorescent concentrators, however, have been found to be not as cost effective for power production and so far have only been used in consumer products, such as clocks. The static concentrators do not use any tracking mechanism, but they should have a sufficiently large entrance aperture. The concentration ratio, the ratio of the concentrator's area of aperture to the area of the receiver of static concentrators, is low, up to about 5, but this might be attractive in locations where technological resources are limited (Green 2004, Twidell & Weir, 1986, Boyle, 1996, Wrixonet *et al.*, 1993, Markvart, 2000).

Keeping in mind the above discussed factors a simple PV system with a simple support system with variable inclination angles was designed, fabricated and investigated (Pillay, Karimov, 2004, Pillay *et al.,* 2005). Research results are implemented for the utilization of solar energy in the remote places. It was observed that the inclination angle of the module affects its output of electric power. In this paper, the design and investigation of a photo-voltaic system with variable inclination angles of solar modules is presented.

EXPERIMENTAL SET-UP

The experimental investigation reported in this paper was carried out in February 2009 at the campus of GIK Institute in Pakistan where the latitude is 34^o N. For the experiments, mono-crystalline silicon cell modules were used. The dimensions of each module were 122cm x 30.5cm and 64cm x 64cm with a total area of 0.37-0.39m^2 and 0.41m^2. The current-voltage characteristics, open-circuit voltages and short-circuit currents of the selected modules were measured under natural conditions. The fill factor of the modules determined was $FF = 0.75$. The experiments were conducted on clear days and days with variable clouds. Modules were fixed at different inclination angles, i.e. 23^o, 34^o

and 45^o at the latitude of location (34^o), and plus or minus half of the solar declination (23^o). The global irradiance at different inclination angles (23^o, 34^o and 45^o) of the sensor was estimated accordingly. The electrical parameters and characteristics of the modules of the PV system investigated were used for the design and implementation of a simple PV modules support to easily change the modules inclination angles seasonally (Fig. 2).

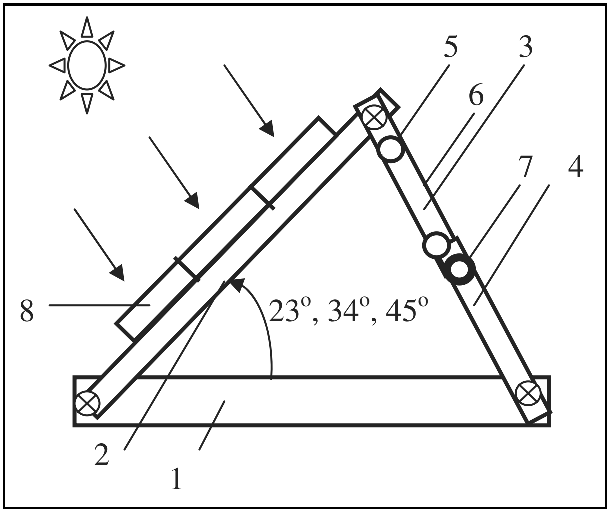


Figure 2: A simple PV system's support with modules of variable inclination angles: (1) horizontal base, (2) inclined unit, (3,4) variable length arm, (5,6,7) fixings for change in angle of 23^o, 34^o and 45^o), (8) modules

On each of these supports on average, 5 to 6 modules were installed. The total number of the modules in the PV array and the supports were 180 and 34, respectively. This support consists of a horizontal base (1) an inclined unit (2), a variable length arm (3 and 4 are two elements of the arm), and the fixings (5, 6 and 7 for fixing at the inclination angles of 23^o, 34^o and 45^o. The total number of the variable arms was 68, i.e. two for each support. The modules (8) were installed on the inclined unit. The arm was made from a beam. The fixings allowed change in the arm's length, hence change in the inclination of the modules. The arm's length is changed by the motion of the arm's elements 3 and 4, along with their axes and fixing at the proper position. The elements of the support were made from steel. It is concluded that compared to the totally fixed modules' array this support has very few differences; actually it is variable to the arm's length only. It means that the present array supports' arms can be easily remade in order to make the support with variable modules inclination angles with few changes, as it was realized in practice by the authors (Fig. 3). Approximately one and one half hour was calculated to change the inclination angle of all modules of the PV array seasonally.

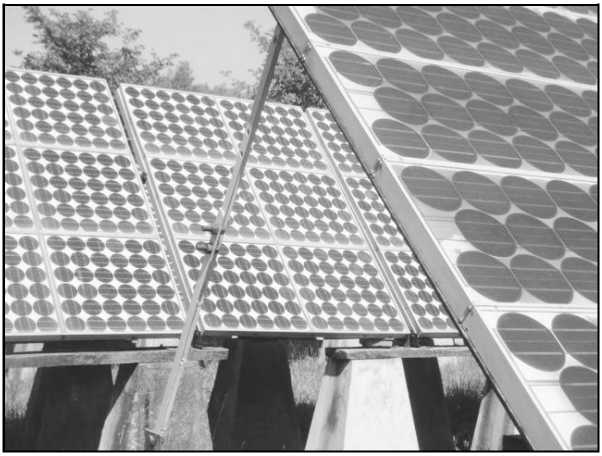
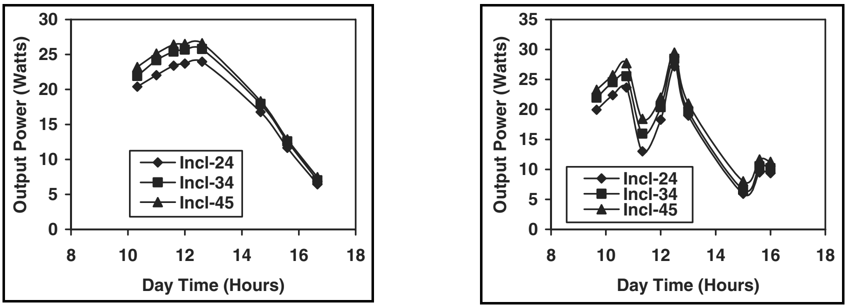


Figure 3: Photovoltaic array with variable modules inclination angles

The PV system's modules were faced to the south with variable inclination angles. Variation of the ambient temperature during the day time was in the range of 15°C-21°C. For the measurements of voltage, current, temperature and irradiance, conventional meters were used.

RESULTS AND DISCUSSIONS

Fig. 4 shows the output power measured during a day for one module for one clear and one day with variable clouds using different module's inclination angles: 23°, 34° and 45°. It is observed that the output power is the maximum at an inclination of 45° and minimum at 23° during winter time, i.e. February 2009. On average, the module's output power increases in the range of 11%-13% and 9%-20% with increases in the inclination angle during a clear and variably cloudy day, respectively.



(a) (b)

Figure 4: Output power vs day time relationship for the one module for different module's inclination angles, i.e. 23°, 34° and 45°: (a) at clear day, (b) variable cloudy day

Fig. 5 shows current-voltage characteristics (I-V) of the module measured at noon time (12:00) during a clear day for different module's inclination angles: 23°, 34° and 45°. For the case of a variable cloudy day, the I-V characteristics were approximately the same. It is well-known that with an increase of irradiation the output current and voltage of the module increases (Markvart 2000). It is seen from Fig.5 that the effect of inclination angle to the I-V characteristics is the same as the effect of an irradiation increase.

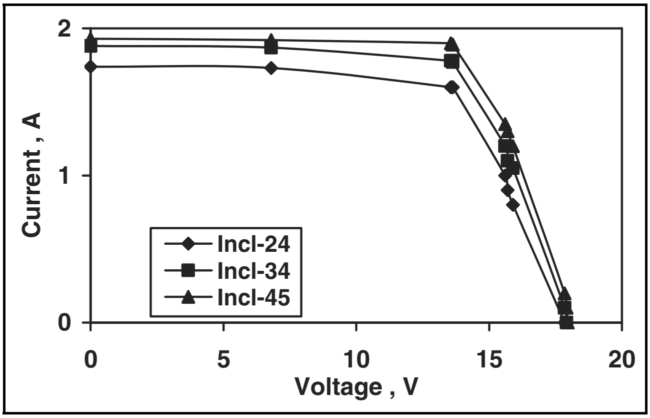


Figure 5: Current-voltage characteristics of the module measured at noon time (12:00) on a clear day for different module's inclination angles, i.e. 23°, 34° and 45°

Fig. 6 shows global irradiance measured for the sensor's inclination at noon time (12:00) during a variably cloudy day. The irradiance sensor was placed at the same inclination angles as the module. It is seen that the global irradiance on an inclined surface also increases with an increase in the inclination angle. An analogous relationship was obtained for the clear day experiments.

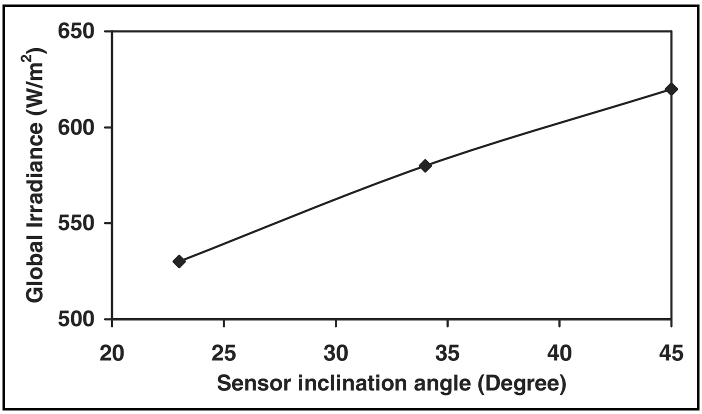


Figure 6: Global irradiance for sensor's inclination angles 23°, 34° and 45° at noon time (12:00) for a variably cloudy day

Fig. 7 shows the module's output energy with the variation in the inclination angle during a clear and a variably cloudy day. It is seen that the output energy increases with the increase in the inclination angle on 12%-19% and is concluded due to the increase of global irradiance (Fig. 6).)

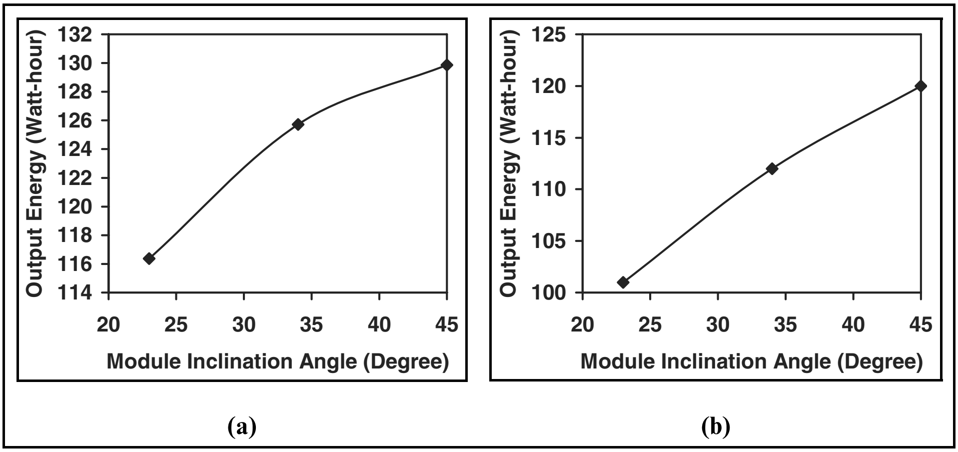


Figure 7: Module's output energy for module's inclination angles 23°, 34° and 45° for; (a) a clear day, (b) a variably cloudy day.

As beam irradiance is maximum in winter time at the inclination angle of the receiver that is above of the latitude on approximately on 11° (Markvart, 2000), we may guess that the further increase of the module inclination angle (Fig.6 and Fig.7) will bring a decrease of the irradiance and output energy accordingly. Irradiation vs. receiver's or module inclination angle studied during a year (Markvart, 2000) showed that, for example, in the case of Barcelona (Spain) in March and September the maximum daily irradiation was when the inclination angle was equal to the latitude (40°); whereas at the inclination angles of 20° and 60°, irradiation was the maximum from April to August, and October to February. The investigations of irradiation vs. output energy at different modules' inclination angles was done in November 2004 (Pillay & Karimov, 2004, Pillay *et al.,* 2005) and in March 2006 (Karimov *et al.*, 2006, Ghias *et al.,* 2007, Karimov *et al.,* 2007**)**, by the present authors with the same modules and in the same place (GIK Institute, Topi, Pakistan), Results obtained are found in good agreement with the reference data. Processing of all these data was used to draw the approximate daily output energy of the module in GIK Institute over the year for the selected angles of 23°, 34° and 45° of the module inclination (Fig.8). It is seen that at the module inclination angles of 23°, 34° and 45° the output energy is maximum in April-August, March and September, and October-February, respectively.

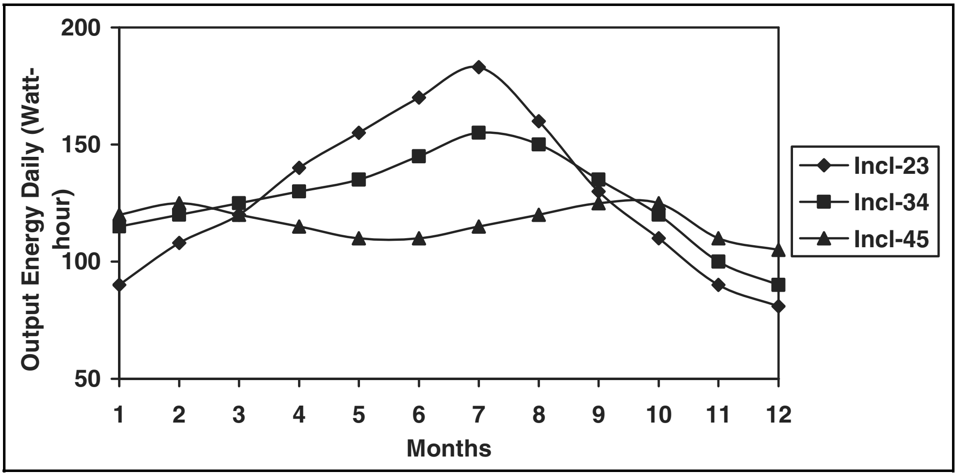


Figure 8: Daily output energy of the module in GIK Institute over the year for the selected module inclination angles of 23°, 34° and 45°. (1 is January and 12 is December)

The presented results show that the PV system with variable modules' inclination angles provides larger amounts of energy when compared to the fully fixed PV system. The cost of an electricity-generating system is considered an important parameter as the cost of unit of the generated electricity is a valuable figure. Based on the results, it is concluded that the cost of electricity in the PV system with variable inclination angles will be cheaper. Electricity cost can be determined by the following relationship (Markvart, 2000):

$$\text{Electricity cost (\$ / kWh)} = \text{ALCC (\$ / year) / Electricity supplied (kWh / year)}, \quad (1)$$

where ALCC is the 'Annualized Life-Cycle Cost'. The electricity supplied each year can be estimated as:

$$\text{Electricity per year} = G \times A\eta \times \eta_t \times 365(kWh), \quad (2)$$

where G is the average annual irradiation in kWh/m^2-day (5.5 kWh/m^2-day), A is array area in m^2 (0.37 m^2), η is the module's efficiency (11%), η_t is total system efficiency (90%), and 365 are the number of days in a year. Expression 1 and 2 shows that if the electricity supplied increases due to the increases of average annual irradiation, it will result in a decrease of the electricity cost accordingly. For example, if the output electric energy increases with the increase in the inclination angle on 12%-19% (Fig. 7), the electricity cost will decreases.

CONCLUSION

After detailed investigation of a PV module using different inclination angles during a clear and a cloudy day, it was observed that

- the daily produced electric energy per module increases 12%-19% with an increase in the inclination angle from 23^o to 45^o during winter (February 2009).
- electricity cost produced by the PV system decreases with an increase in the modules' inclination angle.
- simple PV modules support was designed to easily change the modules' inclination angles. On each of these supports 5 to 6 modules were installed and approximately one and one half hour was needed to change the inclination angle of all 180 modules of the PV array seasonally.

ACKNOWLEDGEMENT

The authors acknowledge the Pakistan Science Foundation for funding to complete this project, and the GIK Institute for support to carry out this research work.

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Submitted : *11/3/2009*
Revised : *10/8/2009*
Accepted : *13/9/2009*

التحقق في نظام الجهد الضوئي مع تغير زوايا ميل وحدة قياس الطاقة الشمسية

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خلاصة

تشرح هذه الورقة تصميم وتحقق لنظام الجهد الضوئي مع تغير زوايا ميل وحدة قياس الطاقة الشمسية. إن خواص الجهد – التيار (I - V) لوحدة قياس بلورة واحدة قد تم التحقق فيه في الظروف الطبيعية. إن نظام PV يشتمل على 180 وحدة لمساحة تتراوح ما بين 0.37 - 0.39م^2. إن زاوية الميل لكل وحدة قياس مع المستوى الأفقي هي: 23° 34° و45° إن خط العرض لموقع محطة PV هو 34° شمال. لقد أجريت التجارب في أيام صافية ومتغيرة الغيوم. لقد تم ملاحظة أن هناك زيادة ما بين 12 – 19٪ في إنتاج الطاقة الكهربائية مع الزيادة في ميل الزاوية في فترة الشتاء أي فبراير 2009.

إن كفاءة الوحدات تراوحت ما بين 11 – 12٪ عند تغيير زوايا الميل. لقد تم تصميم وحدات دعم PV بسيطة لكي يسهل تغيير وحدة ميل الزاوية. إن العدد الكلي للدعائم كان يساوي 34 وقد تم تركيب 5 – 6 وحدة قياس على كل وحدة دعم.