Dual-Axis Solar Tracking System for Maximum Power Production in PV Systems

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ABSTRACT: The power developed in a solar energy system depends fundamentally upon the amount of sunlight captured by the photovoltaic modules/arrays. This paper describes a simple electro-mechanical dual axis solar tracking system designed and developed in a study. The control of the two axes was achieved by the pulses generated from the data acquisition (DAQ) card fed into four relays. This approach was so chosen to effectively avoid the error that usually arises in sensor-based methods. The programming of the mathematical models of the solar elevation and azimuth angles was done using Borland C++ Builder. The performance and accuracy of the developed system was evaluated with a PV panel at latitude 3.53^{o} N and longitude 103.5^{o} W in Malaysia. The results obtained reflect the effectiveness of the developed tracking system in terms of the energy yield when compared with that generated from a fixed panel. Overall, 20%, 23% and 21% additional energy were produced for the months of March, April and May respectively using the tracker developed in this study.

KEYWORDS: solar tracking; photovoltaic system; dual-axis; azimuth; elevation angle, DAQ card

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I. INTRODUCTION

Today, renewable energy has successfully grabbed so much global attention in the energy production circle. The three major drivers identified to be responsible for this development, among others, include: (i) the continuous rise hitherto in the international oil prices (ii) the need for the future energy security given the fast decrement in the fossil fuels reserves, and (ii) the need to preserve the environment from further degradation caused by the greenhouse gas emissions arising from combustion of the fossil fuels. (Akorede *et al*, 2012)

Among the renewable energy resources, solar energy appears to be the most powerful resource that could be used for power generation. It is relatively available for a continuous period of time from sunrise to sunset in most countries. However, the amount of energy that could be produced from solar, most especially using the fixed-type solar panel, is limited due to the changing spatial distribution of the sunlight (Yao, *et al*, 2014, Famoso, *et al*, 2015). To maximize the amount of power produced from solar energy, it is crucial to ensure that the incident sun rays are always perpendicular to the surface of the solar panel. Therefore, to have an approximately constant energy production throughout the day, it is necessary that the photovoltaic panels change orientation throughout the day to follow the path of the sun in the sky. This could be achieved by a means of an automatic solar tracking system.

Initially, the majority of PV systems used worldwide were the fixed type solar panels (Karimov *et al*, 2005). The major deficiency of this method is low efficiency since the sun keeps moving and the radiated solar could not be maximally captured by the solar panels. Since the power developed in solar energy systems depends fundamentally upon the amount of solar energy captured by the solar PV modules, it therefore makes clear the imperativeness of a tracking system to enable maximization of the available solar energy during the day time. A solar tracker improves the efficiency of solar energy conversion system by following the trajectory of the sun every day throughout the year (Markvart, 2000).

Lots of research works have been carried out in this area and a number of different approaches for tracking the sun have been proposed by various researchers (Garrison, 2002, Berenguel *et al,* 2004, Popat, 1998). For example, light source sensors, light intensity sensors, intelligent vision techniques, and charge-coupled device (CCD) equipment have been applied to compute the daily sun radiation in order to estimate the volume of solar energy available at any time of the day. In the same vein, various methods have been proposed for optimising the tilt angle and orientation of solar panels, to ensure maximum utilisation of solar energy for power production (Lynch & Salameh, 1990, Wentzel & Pouris, 2007).

By and large, the results showed that, using mathematical models to optimize the tilt angle and orientation of the solar collector, an annual increase of more than 5% of solar radiation could be captured compared to the case in which the modules were permanently fixed on a horizontal surface. In (Abdallah & Nijmeh, 2004), the improvement in the performance of a solar cooker during summer was found to be as much as 40% for higher elevation angles with the proposed tracking algorithm by the authors. In another study (Markvart, 2000), it was revealed that by continuously adjusting the tilt angle to track the sun's movement, a solar

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collector is capable of increasing the amount of solar energy produced by more than 40%.

From the literature surveyed on this subject, closed-loop systems with photosensors are traditionally used. The photosensors are responsible for discrimination of the sun position and for sending electrical signals, proportional with the error, to the controller, which actuates the motors to track the sun. Many authors have adopted this method as a basis in the construction and design of such systems (Karimov *et al*, 2005, Baltas *et al*, 1986, Dobon, *et al*, 2003]. However, the downside of this approach is that the sensors may introduce errors in the detection of the actual position of the sun for varying weather conditions (Abdallah & Nijmeh, 2004, Alexandru & Pozna, 2008).

Other possible solutions are the open loop systems based on mathematical algorithms that provide predefined parameters for the motors depending on the sun's positions on the sky dome. These positions can be precisely determined because they are functions of the solar angles that can be calculated for any local area (Abdallah & Nijmeh, 2004, Alexandru & Pozna, 2008, Alexandru & Comsit, 2007, Roth *et al*, 2005). By using this control technique, the errors introduced by the use of the sensors may be avoided.

This paper is primarily concerned with analysis and simulation of a dual axis solar tracker. The work done in this study is a preliminary approach to developing a solar tracking system for heavy solar modules. The benefit of the approach used in this study is that it could track the sun's position even in cloudy weathers.

II. MATHEMATICAL MODELLING

A. Solar elevation angle

The elevation angle, often used interchangeably with the altitude angle, is the angular height of the sun in the sky measured from the horizontal plane. At sunrise in the morning, the elevation is 0° and it is 90° when the sun is directly overhead. The latter is called maximum elevation angle – an important parameter in the design of photovoltaic systems (PVedu, 2012). The elevation angle, which varies throughout the day, depends on the latitude of a particular location and the day of the year. While the maximum elevation angle is used even in very simple PV system design, more accurate PV system simulation requires the knowledge of how the elevation angle varies throughout the day. The elevation can be found using the expression in eqn (1).

$$\beta_S = \sin^{-1}(\cos\gamma\cos\delta\cos\phi + \sin\delta\sin\phi) \qquad (1)$$

where γ = the hour angle, ϕ = local latitude, and δ = declination angle of the Earth.

B. Solar azimuth angle

In order to determine the position of the sun at a given location on a particular date and time, it is necessary to know the angle of elevation or inclination of the sun with respect to the plane and the angle of azimuth. The azimuth angle is the compass direction between the true north and the projection of the sun rays on to the horizontal plane (Kacira *et al*, 2004). At solar noon, the sun is always directly south in the northern hemisphere; hence the solar azimuth angle, α_S is 0^o. The azimuth angle varies throughout the day. At the equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thereby making the azimuth angles 90° at sunrise and 270° at sunset (PVedu, 2012) as shown in Figure 1. Solar azimuth can be computed using the expression in eqn (2). However, to determine this angle, the declination of the Earth, δ with respect to the equator is first calculated with eqn (3).

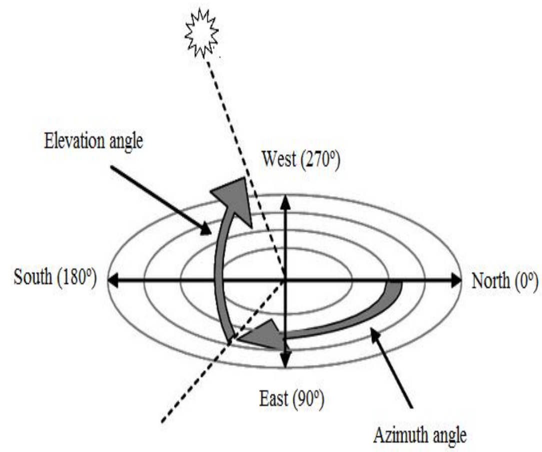

Figure 1: Solar azimuth

$$\alpha_S = \cos^{-1}\left(\frac{\sin\delta\cos\phi - \cos\gamma\cos\delta\sin\phi}{\cos\beta_S}\right) \qquad (2)$$

$$\delta = 23.45^o \sin\left[\frac{2\pi}{365}(284 + d)\right] \qquad (3)$$

where d is the day of the year.

C. Solar irradiance on a tilted surface

Even though the solar radiation incident on the Earth's atmosphere is relatively constant, the irradiance received at the Earth's surface varies widely due to a few factors. These include atmospheric effects, including absorption and scattering; local variations in the atmosphere, such as water vapour, clouds, and pollution; the latitude of the location; and the season of the year as well as the time of the day (PVedu, 2012). In PV system design, it is essential to know the amount of sunlight available at a particular location in a given time. The two common methods which characterise solar radiation are the solar irradiance and solar insolation. The solar irradiance is an instantaneous power density in units of kW/m^2. It varies throughout the day from 0 kW/m^2 at night to a maximum of about 1 kW/m^2 in the day time. The solar irradiance is strongly dependent on location and local weather.

The total hourly solar irradiance incident on the surface of a tilted PV module basically consists of three components. These include the direct beam, I_{BD}, which is the major component; diffuse irradiance I_D, and the reflected irradiance I_R. A commonly used model to calculate the direct beam given by ASHRAE (Handbook, 2001) is presented in eqn (4).

$$I_{BD} = \left(1160 + 75\sin\left[\frac{2\pi}{365}(d-275)\right]\right)e^{-km} \quad (4)$$

where k and m are air mass ratio and optical depth respectively. These are computed using eqns (5) and (6) respectively.

$$k = 0.174 + 0.035\sin\left(\frac{2\pi}{365}(d-100)\right) \quad (5)$$

$$m = \frac{1}{\sin\beta_S} \quad (6)$$

Now, the amount of direct-beam solar irradiance perpendicular to the tilted surface is determined by eqn (7)

$$I_B = I_{BD}\left[\cos\beta_S\cos(\alpha_S-\alpha_P)\sin\tau + \sin\beta_S\cos\tau\right] \quad (7)$$

Given that CI_{BD} is the diffuse irradiance on the horizontal surface, and tilted surfaces can only see some part of the sky, the diffuse irradiance on the plane of the tilted surface is determined as presented in eqn (8).

$$I_D = CI_{BD}\left(\frac{1+\cos\tau}{2}\right) \quad (8)$$

where C is given by

$$C = 0.095 + 0.04\sin\left(\frac{2\pi}{365}(d-100)\right) \quad (9)$$

Similarly, the ground reflected irradiance on the tilted surface is determined by eqn (10), where ρ is the ground reflectance and τ is the tilt angle of the surface.

$$I_R = \rho I_B(\sin\beta_S + C)\left(\frac{1-\cos\tau}{2}\right) \quad (10)$$

Therefore the total irradiance received on the plane of a tilted PV modules or array at any time of the day is expressed in eqn (11), by combining eqns (7), (8) and (10).

$$I_T = I_B + I_D + I_R \quad (11)$$

III. Design And Construction Of The System

The design of the solar tracking system in this study is carried out in such a way to move the PV panels in both axes. In the study, the main rotaters for both axes of the solar tracker are driven by two power window motors of 12 volts each. These motors are so chosen for high torque and economic reasons. The motors will be controlled using digital outputs from the data aquistion (DAQ) card driven by a program written in the Borland C++ Builder. The layout of the tracking system is shown in Figure 2

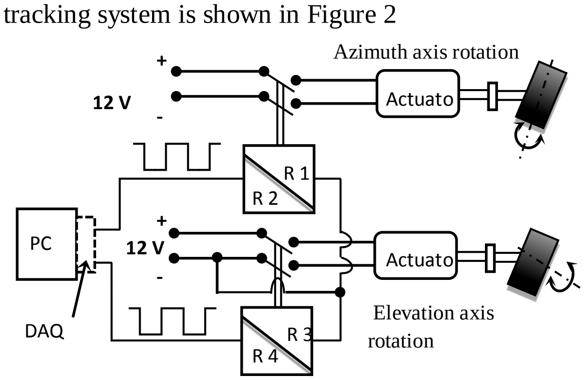

Figure 2: The layout of the solar tracking system.

The system comprises of a PC, DAQ card, four relays, a lead acid battery and two window power motors. The program written in C++ when run on the PC generates some pulses based on the computed values of solar azimuth and elevation, which trigger the relays in a sequential order. Relays 1 and 3 use the positive pulses to rotate the PV panel in both azimuth and elevation axes respectively, while the negative pulses are used to drive Relays 2 and 4 to reset the two axes back to their initial states after the working hours of the day. The battery is used to power the two motors.

The calibration of the rotation of the mechanism for both axes was manually carried out. The time taken for the elevation axis to rotate a complete cycle of 180^o was experimentally determined as approximately 90 s. Therefore the time required for the elevation axis to rotate 1^o is 0.5 s. This is the time required for the power window motor to rotate for 1°. Using the same approach, the time taken for azimuth to complete a rotation of 180^o is obtained as 120 s, which gave 0.66 s for a 1^o rotation. A simple protractor is placed right beside the panel of the dummy solar tracker to enable the user read the elevation angle. Bicycle gears and chains are used as the rotating tools for both axes in order to minimize the torque and improve the accuracy of the rotation.

A. Graphical User Interface Design

The graphical user interface (GUI) developed, using Borland C++ Builder, for the system is displayed in Figure 3. The azimuth and elevation angles are calculated and displayed in Panel 15 and Panel 16 respectively. The rotation directions of motors 1 and 2 will also show when the motors are in the pause mode. The *START* button is to run the program to start the tracking of the sun. Panels 12, 11 and 10 are to respectively show day, month and year, while N stands for the number of days in the year. Latitude and Longitude of the site are displayed in Panel 13 and Panel 14 accordingly. Panels 3, 4 and 5 will show the current time; hour, minute and second respectively. The function of Edit 1 and Edit 2 is to accept the operation starting time.

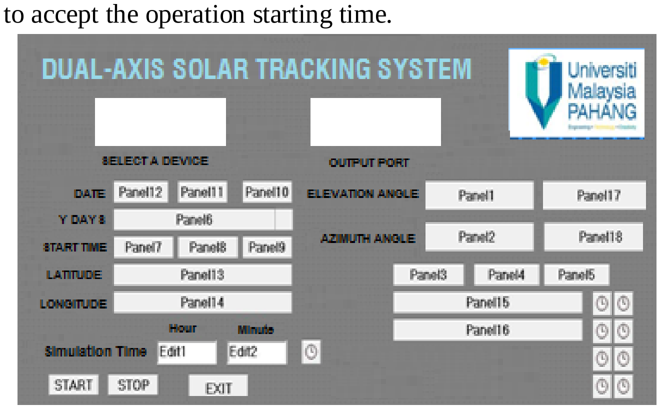

Figure 3: Graphical user interface (GUI) for the tracking system.

The control of the solar tracker is achieved by using Borland C++ Builder. The software is so chosen in the study because it contains the required features which include the application of the mathematical formulas of the azimuth and elevation angles that control the simulation of the tracker, as well as the necessary components for the interface between the motors and the PC via USB DAQ card. The solar elevation and azimuth angles computed using eqns (1) and (2) respectively are determined for each day of the year, which correspond to the angle values of the mechanism of the tracking system. The flowchart of the program developed for the dual-axis sun tracking system is shown in Figure 4.

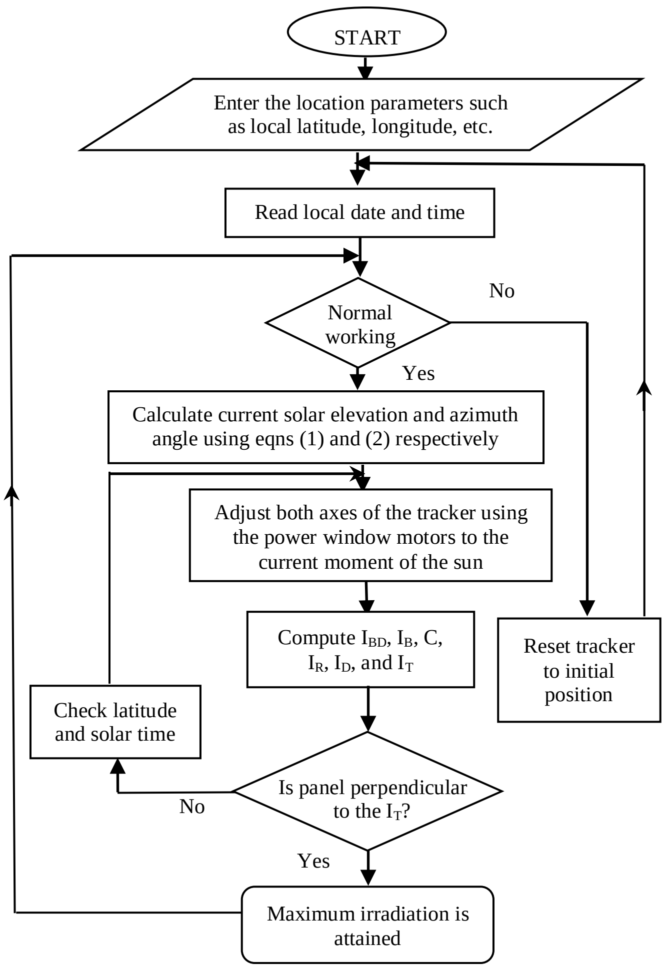

Figure 4: Flowchart of the software.

B. Electronic Circuit Design and Etching

The voltage output from the DAQ Card is 3.28 V, which is insufficient to drive each of the 12 V DC motors. Hence, there is a need to have a motor driver circuit as an interface. The circuit was designed and simulated using the Proteus software to ascertain its workability. The PCB board of Figure 5 was designed and prepared with the aid of the Eagle Layout Editor 6.2.0 software.

C. Hardware Development

The two-axis solar tracker was made of steel while the frame was of aluminium. Two axles are designed to rotate the solar module in both axes. The module can rotate freely in both clockwise and anti-clockwise directions. Two 12 V DC power window motors were chosen to rotate the axles. The power window motors have high torque and moderate speed. Thus, the rotation of motors is slowed down from small gear to large gear. Light steel was used to construct the base that holds the solar module, having established the fact that it is able to withstand the weight and the blowing wind.

The gear weld bellow the solar tracker is connected to the power window gear using chain to cause the azimuth angle rotation. A pole is welded to support the weight of power window motor, the gear, chain, and the PV module. The positioning of the motor, the gear and PV module is essential to balance the weight of the pole. The gear is installed at left and right of pole, while the motor is situated at left to rotate the PV module in right direction.

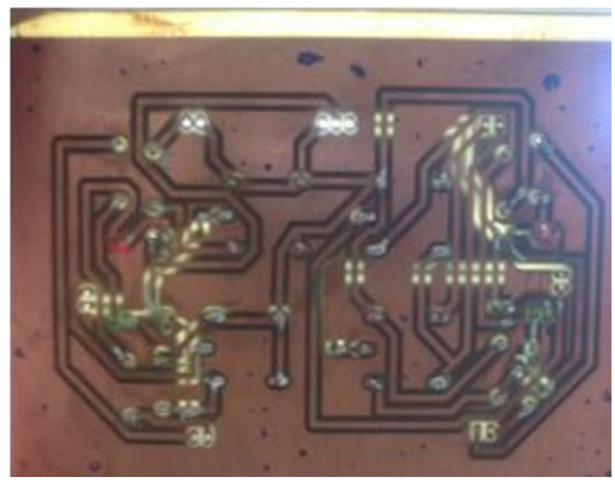

Figure 5: PCB of the electronic circuit.

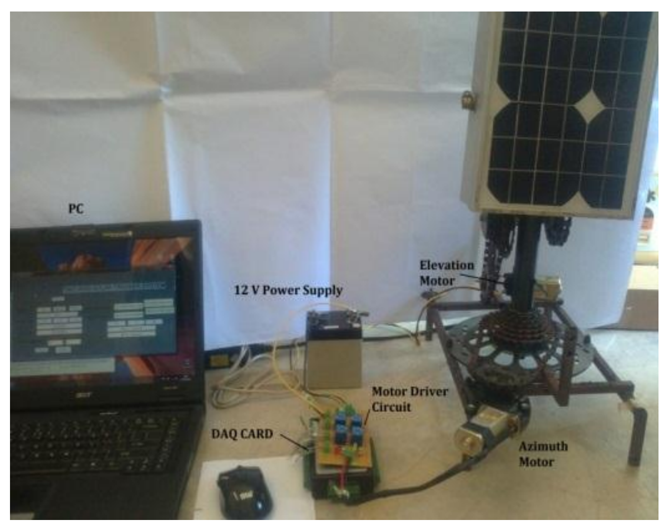

Figure 6: Testing the azimuth and elevation rotations.

D. Hardware and Software Integration

The software and hardware components were integrated together to form a complete system. Borland C++ Builder software was synchronised with the load by using Data Acquisition (DAQ) card. DAQ card USB 4716 is considered suitable because it can control many outputs concurrently. The software sends a command to the motors, which acts as a switching device to turn ON/OFF the motors. The motor driver circuit then connects 12 V power supply and the two power window motors for the azimuth and elevation rotation.

This causes gears to rotate and turn the Photovoltaic (PV) module accordingly. Figure 6 is presented to show the calibration of the gearing system.

IV. Results and Discussion

To evaluate the performance of the developed solar tracker, it was tested on the 17th of March, April and May 2014 at Faculty of Electrical and Electronic Engineering, Universiti Malaysia Pahang open premises. The system control was done on the PC situated at a veranda by running the program starting from 6:00 am until 7:00 pm. The experimental setup is presented in Figure 7.

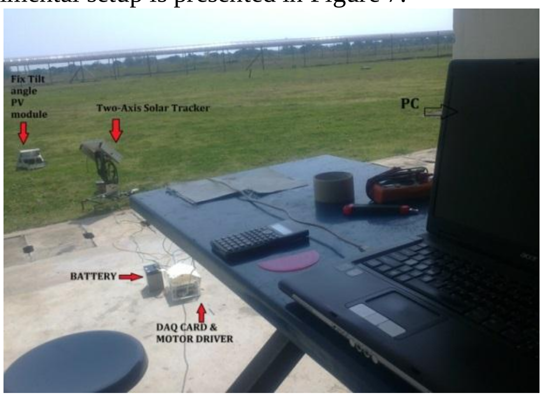

Figure 7: The experimental setup the tracking and the fixed systems.

Readings of the elevation and azimuth angles were taken on hourly basis and are manually plotted in Figures 8 and 9 respectively. Another PV module of a fixed tilt angle was also set up, and its readings were taken simultaneously. The developed system responded to the program control and was able to rotate both axes following the sun's direction. The effect of the tracking could be observed in Figure 10, where the solar power generation from the PV with the developed tracker is higher than that without.

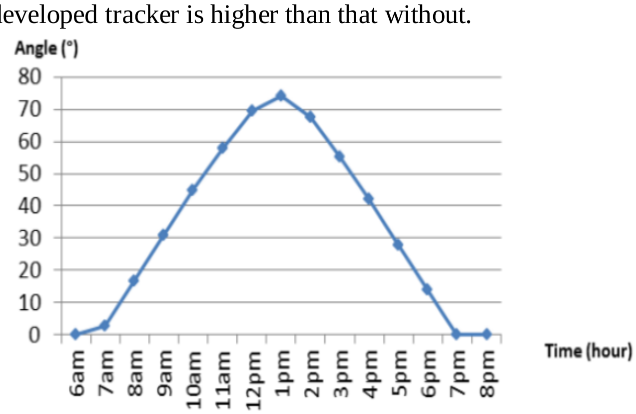

Figure 8: Elevation angle of the sun at the case study site.

The operation of the solar tracker took place only when the sun was above the horizon, i.e. from sunrise to sunset. The default time set for the tracker developed in this study to begin operation is 7:00 am while 7:00 pm was set for it to return to the initial position in readiness for the next day operation. These settings were based on the case study's geographical data, Pekan, Malaysia, whose average sunrise time is 7.15am and 7:00 pm for sunset.

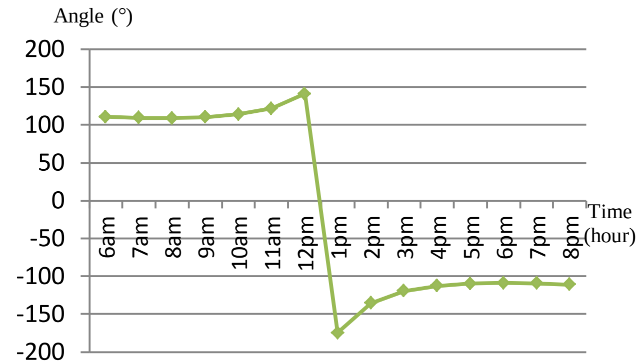

Figure 9: Azimuth angle of the sun of the case study site on May 17, 2014.

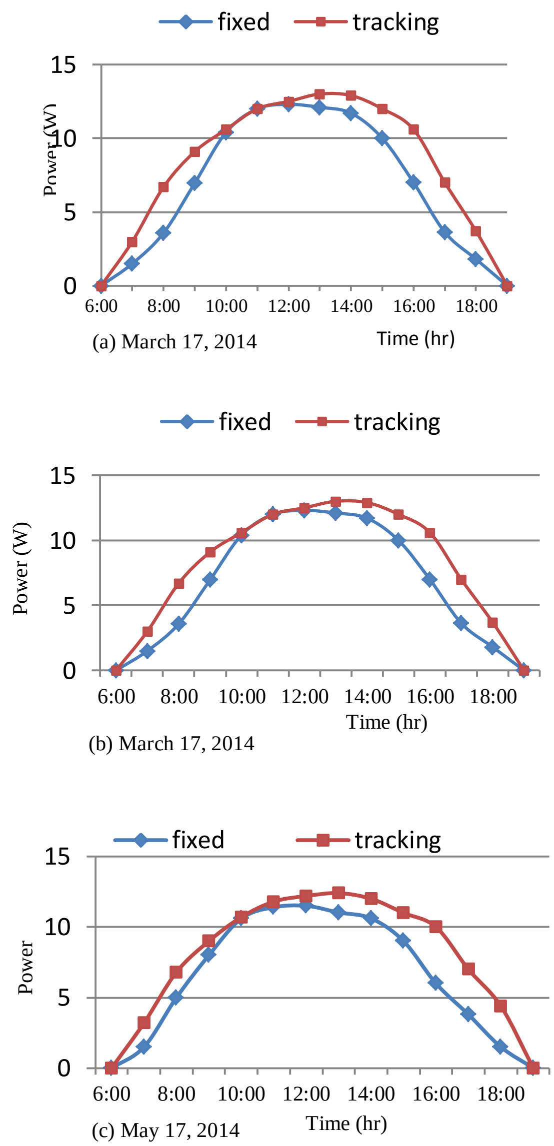

Figure 10: Hourly plots of the energy produced from 20 W solar panels.

However, because the control technique used in this work does not use sensor for the tracking, but was based on mathematical formulas, an initialisation process is required to be carried out after a maintenance action has taken place on the developed tracking system. This action would ensure that the starting position of the tracker is correct, after which it continues to operate autonomously.

The expression to calculate the percentage energy gain is presented in eqn (12). This is necessary to evaluate the effectiveness of the tracking system.

$$PEG = \frac{E_{TR} - \left(E_{FX} + E_{CT}\right)}{E_{FX}} \times 100\% \quad (12)$$

where E_{TR} is daily energy produced with the tracking system, E_{FX} is energy produced without tracking, and ECT is the energy consumed by the tracking system. E_{CT} was estimated at 1.3 Wh, given the rated power of the power window motor of 22 W for a total period of 210 secs (i.e 90 secs for elevation axis and 120 secs for the azimuth axis).

From Figure 10, the daily energy produced by the PV system could be estimated as the area covered by each plot. This was estimated at 92.98 Wh and 113.10 Wh for March 17 2014 for the panel without and with tracking system respectively. April 17, 2014 witnessed the highest energy production with 116.61 Wh and 93.51Wh for with and without the tracking system. Lastly, a total of 89.94 Wh and 110.49 Wh were generated on May 17, 2014 for without and with the tracking system. The percentage energy gain of 20%, 23% and 21% were respectively obtained for the months of March, April and May.

V. Conclusion

This study has successfully developed a user-friendly dual axis solar tracker. The azimuth and the elevation angles of the sun were mathematically calculated on an hourly basis for each day of the year. The values of these parameters were then used to determine the current position and orientation of the sun to be tracked. DAQ card was used to generate pulses, based on the Borland C++ program written to activate the relays coupled to the power window motors that have been mechanically coupled to the two axes of the tracker. The developed system was tested with a solar panel, and the result obtained was compared with a fixed panel. Overall, the tracking system produced additional energy yield of 20%, 23% and 21% for the months of March, April and May 2014 evaluated. These values are comparable with what obtains in the literature.

Given the level of success recorded in this work, further study is planned to reinforce the developed tracking system so as to enable it carry more photovoltaic panels.

References

Abdallah, S. and Nijmeh, S. (2004). Two axes sun tracking system with PLC control. Energy conversion and management, 45: 1931-1939.

Akorede, M. F.; H. Hizam, M. Z. A. Ab-Kadir, I. Aris, and S. D. Buba (2012). Mitigating the Anthropogenic Global Warming in the Electric Power Industry. Renewable and sustainable energy reviews, 16: 2747-2761.

Alexandru, C. and Pozna, C. (2008). Different tracking strategies for optimizing the energetic efficiency of a photovoltaic system, in IEEE International Conference on Automation Quality and Testing Robotics, Cluj-Napoca, 434 – 439.

Alexandru, C. and Comsit, M. (2007). Virtual prototyping of the solar tracking systems, in International Conference on Renewable Energy and Power Quality, Sevilla, 41-42.

Baltas, P.; M. Tortoreli, and P. E. Russell (1986). Evaluation of power output for fixed and step tracking photovoltaic arrays. Solar energy, 37: 147-163.

Berenguel, M.; F. Rubio, A. Valverde, P. Lara, M. Arahal, E. Camacho, and M. LÃ³pez (2004). An artificial vision-based control system for automatic heliostat positioning offset correction in a central receiver solar power plant. Solar energy, 76: 563-575.

Dobon, F.; A. Lugo, J. Monedero, P. Valera, R. Osuna, L. Acosta, and G. Marichal. (2003). First results of the tetra-track system and control electronics, 2: 2050-2053.

Famoso, F.; R. Lanzafame, S. Maenza, P. F. Scandura (2015). Performance Comparison between Low Concentration Photovoltaic and Fixed Angle PV Systems. Energy Procedia, 81: 516-525.

Garrison, J. D. (2002). A program for calculation of solar energy collection by fixed and tracking collectors. Solar energy, 73: 241-255.

Handbook (2001). Fundamentals. American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta.

Kacira, M.; M. Simsek, Y. Babur, and S. Demirkol (2004). Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey. Renewable Energy, 29: 1265-1275.

Karimov, K. S.; M. Saqib, P. Akhter, M. Ahmed, J. Chattha, and S. Yousafzai (2005). A simple photo-voltaic tracking system. Solar energy materials and solar cells, 87: 49-59.

Lynch, W. A. and Salameh, Z. M. (1990). Simple electro-optically controlled dual-axis sun tracker. Solar energy, 45: 65-69.

Markvart, T. (2000). Solar electricity. John Wiley & Sons Inc, New Jersey.

Popat, P. P. (1998). Autonomous, low-cost, automatic window covering system for daylighting applications. Renewable Energy, 13: 146-146.

PVedu (2012). Elevation Angle. Retrieved February 2012 from http://www.pveducation.org/pvcdrom/properties-ofsunlight/elevation-angle.

Roth, P.; A. Georgiev, and H. Boudinov (2005). Cheap two axis sun following device. Energy conversion and management, 46: 1179-1192.

Wentzel, M. and Pouris, A. (2007). The development impact of solar cookers: A review of solar cooking impact research in South Africa. Energy policy, 35: 1909-1919.

Yao, Y.; Y. Hu, S. Gao, G. Yang, J. Du (2014). A multipurpose dual-axis solar tracker with two tracking strategies. Renewable Energy, 72: 88-98.