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DESIGN AND PERFORMANCE OF DUAL AXIS SOLAR TRACKER BASED ON LIGHT SENSORS TO MAXIMIZE THE PHOTOVOLTAIC ENERGY OUTPUT

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ABSTRACT

The effectiveness of solar energy absorption has become an issue in photovoltaic (PV) performance. In addition to environmental considerations such as cloud shadows, the ever-changing position of the sun is a determining factor in maximizing the output of electrical energy from PV systems. This research proposes a design of a dual axis solar tracker to increase energy production and discusses its function to track the sun's location in the effective way. To verify the effectiveness of the proposed system, a test is conducted by comparing the system's performance with a system that does not employ a solar position tracking system know as a fixed system.The test is carried out under several conditions, including on a sunny day, a cloudy day, and a cloudy day with intermittent rain. According to the test results, the solar position tracking system with dual axes is more efficient at generating electrical energy in PV systems. The electrical energy generated is 18.56% higher than that of a fixed system

Keywords: *Dual Axis Solar Tracker, Photovoltaic, Energy Production, Solar Tracker*

1. INTRODUCTION

The energy crisis is a worldwide issue that many countries are grappling with right now. Recently, many countries have tried to deal with the energy crisis. The supply of fossil energy sources has become relatively limited and there has been excessive consumption in the last 30-40 years, thus renewable energy sources, such as solar and wind energy, are the only options to meet energy needs [1] [2]. Solar energy is a clean, pollution-free renewable energy source that does not contribute to global warming. It is widely available practically all around. However, the efficiency of the electrical energy generated has remained an issue. Therefore, there should be solutions to increase the production of electricity output from solar energy sources. Solar energy can be converted into electricity by utilizing solar panels. However, the intensity of solar radiation, ambient or environmental temperature, wind speed, and humidity have a significant impact on how much electricity solar panels can produce [3][4]. When the sun is perpendicular to the solar panels' surface during operation, the electrical energy generated from them is greatest. The amount of electrical energy produced by solar panels will be maximized if the sunlight is perpendicular to the surface of the solar panels during their operations. The amount of electrical energy produced by solar panels will be maximized if the sunlight is perpendicular to the surface of the solar panels during their operations. This condition can be achieved if the solar panel's surface can track the sun's position from morning to evening. This tracking idea is also referred to as a solar tracking system. In general, the tracking approach, the number of motion axes, the presence and function of the electronic system, and the presence of feedback can all be broken down into different components of the solar position tracking system [5].

The tracking strategy divides it into three categories: chronological, sensor-based, or a combination of both [6]. The chronological technique is functions at a constant angle throughout the day and month. The motor or actuator's rotation speed is set at a slow condition in one rotation per day (15 degrees per hour) [7]. The system requires more energy to run continuously throughout the day, and it is inefficient on cloudy days [8]. Additionally, optical sensors such as light-dependent resistors (LDR), light optical sensors, and light intensity sensors are also employed in the sun position tracking system [9], with the LDR sensor being the most frequently used. This sensor converts the light captured by the sun into a voltage value, which is then utilized as an input in the algorithm that tracks the sun's position. The surface of the solar panel will be shifted to the area of the sensor that receives the highest illumination value. A hybrid system is the one that combines the use of chronological and sensor methods. According to the test results, the hybrid system performs 13.44% better than the system that does not track the sun's position [10].

The solar tracking system can be categorized as one axis or two axes depending on how many axes of motion are being utilized to track the location of the sun. A single-axis sun position tracking system only tracks the sun along one axis, usually from east to west. The two axes will move in opposite directions from north to south and east to west, respectively, to follow the path of the sun. Furthermore, Vertical single-axis tracker (VSAT), Horizontal single-axis tracker (HSAT), Tilted single-axis tracker (TSAT), Polar-altitude dual-axis tracker (PADAT), Azimut-altitude dual axis tracker (AADAT) are the different types of solar position tracking systems based on the number of axes of movement [11][12]. In addition, an electronic system as a control system is also utilized in the sun position tracking so that the system can operate properly.

According to research results on the use of dual axes with closed loop control by applying the concept of the Astronomical Almanac (AA) Algorithm in tracking the sun's position, this system can perform up to 13.9 percent better than fixed systems and 2.1 percent better than optical tracking systems [13]. Comparing closed and open loop tracking systems, where closed loop is developed using LDR and open loop is developed using an algorithm. The study shows that the open-loop system gained 28.5%, while the closed-loop system tracking gained 33% [14]. Solar position tracking systems frequently employ both open loop and closed loop control schemes. Although open loop control is easier to use and less expensive, it is less effective at resolving steady-state errors [15]. The presence of a feedback system, which is a feedback signal from a variable output, is the most essential part of a closed loop control system. The sensor is also a crucial element for determining the precise sun position, giving feedback to the tracking algorithm, and subsequently causing the tracking position to be reoriented towards the sun [16].

Despite the use of solar PV energy having many benefits, however, this system is still a long way from displacing conventional sources. It is still difficult to maximize the power output of photovoltaic (PV) systems in areas with low solar radiation. Therefore, more innovative technologies are still required to be developed to enhance the performance of PV materials.

The main issue with PV systems is their efficiency in producing electrical energy. Many factors, such as weather and ambient temperature, influence the resulting output. Aside from that, the movement of the sun from morning to evening, as well as the direction of sunlight, have become essential factors that also influence the its efficiency.

The location of the PV system will affect the direction of arrival and changes in solar radiation. More electrical energy can be generated when the surface of the solar panel is perpendicular to the direction of the sunlight. A dual axis solar tracking system is one method for ensuring that the surface of the solar panel is remain aligned perpendicular perpendicular to the direction of the sun's rays. It is able to orient itself towards the sun so that the panel can be in direct contact of the sun for maximum power generation. Although there is a change in the position of the sun from morning to evening and the influence of shadows, especially shadows from clouds.

In this research, a feasible method of system design and module construction for the dual-axis solar tracker is developed. The developed system aims to track the movement of the sun's position. This tracking system maintains the position of the surface of the solar panel to always be perpendicular to the direction of the sun's rays. Apart from that, this system also functions to overcome the problem if the sunlight that leads to the surface of the solar panel is blocked by clouds, the solar tracker will direct the surface of the solar panel to the highest position of solar radiation so that the solar panel will always absorb the maximum sunlight.

This system appears to be promising in terms of maximizing power output since it is not only designed to be able to track sunlight but also constructed at a reasonable cost.

The proposed system is designed and built with simple and low-cost components. The tracking of the sun's position is controlled with an Arduino Mega 2560 with four LDRs that act as sensors to detect differences in sunlight illumination. This tracking system has a vertical and horizontal axis that allows it to track the sun's movement, ensuring that the solar panel's surface is always perpendicular to the sun's rays. The sensor's difference in illumination from sunlight is read by the Arduino Uno, which is then processed and gives a trigger to the motor as an actuator to move towards the highest sunlight illumination. Although there is a shadow that covers the sun's light that leads directly to the surface of the solar panel from morning to evening, the sensor will still detect the sunlight and the actuator will still direct it to the highest illumination from the detected sunlight. As a result, the perpendicular position between the surface of the solar panel and the sun is always maintained from morning to evening.

1.1. Mathematical Modeling of PV Module

Photovoltaic functions to convert photon energy from solar radiation into direct current (DC), with the amount of electrical energy produced depending on the level of radiation and temperature [17][18]. In order to maximize the energy extracted from the PV module as well as to obtain the current and voltage characteristics of the PV array, mathematical modeling is required. Equation (1) illustrates the I-V characteristics for PV modules formed from series-connected PV cells based on a single exponential model [19].

$$I_l = I_{PV} - I_o\left[exp\left(\frac{q(V+I_lR_s)}{N_sAkT} - 1\right)\right] - \left(\frac{V+N_sI_lR_s}{N_s R_p}\right) \quad (1)$$

1.2. PV Cell Module

Figure 1 shows the equivalent circuit of the PV model to convert photon energy into electrical energy. In Figure1, the current Kirchhoff's law equation applies as in equation (2).

$$I_{PV} = I_d + I_p + I_l \quad (2)$$

Where I_{PV} is the photocurrent generated by sunlight and I_d is the diode current. I_l is the current generated by the PV cell while I_p is the leakage current value from the *p-n* junction.

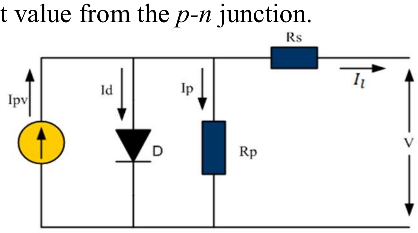

Figure 1: PV Equivalent Cell Circuit

Diode current can be calculated using Equation (3) and saturation current (I_o) can be determined using Equation (4) [19].

$$I_d = I_o\left[exp\left(\frac{q(V+I_lR_s)}{N_sAkT} - 1\right)\right] \quad (3)$$

$$I_o(T) = \frac{I_{scr}(T_{ref})+K_i\Delta T}{exp[q \quad oc(T_{ref})+K_v\Delta T)/AkT]} \quad (4)$$

where,

k : Boltzmann constant (1.3806 x 10 $^{-23}$ J/K)
q : electron charge (1.60217 x 10^{-19} C)
T : module's temperature
R_s : series resistance value
A : ideal diode factor value (1.1<A< 1.6)
I_{scr} : short-circuit current value of the PV cell (can be found in the product datasheet.
K_i : short circuit temperature coefficient value at the time of short circuit (A/K)
K_v : temperature coefficient value when the voltage is open (V/K)

Equation (5) can be used to calculate I_{PV} value.

$$I_{PV} = G\ x\ [I_{scr} + K_i\Delta T] \quad (5)$$

Where G is the incident illumination of the PV module (kW/m2), and I_p can be calculated using equation (6).

$$I_p = \frac{V+N_sI_lR_s}{N_sR_p} \quad (6)$$

1.3. PV Module and Array

PV cells are installed in series and parallel in a PV module to obtain a higher voltage and power value. As shown in Figure 2, the series and parallel combination of PV cells is known as a module or panel, while the series and parallel combination of modules is known as a PV array. The relationship between the PV module's output current and voltage can be expressed as equation (7), while the value of the PV array's output current and voltage can be expressed as equation (8) [20].

$$I_m = I_{ph} - I_r\left[exp\left(\frac{q(V_m+R_sI_m)}{N_skT\alpha}\right) - 1\right] - \frac{V_m+R_sI_m}{R_{sh}} \quad (7)$$

Where V_m and I_m represent the PV module's voltage and current, respectively, and R_s and R_{sh} represent the series and parallel resistances. I_r is the saturation current value of the diode, and α is the ideality factor of the diode.

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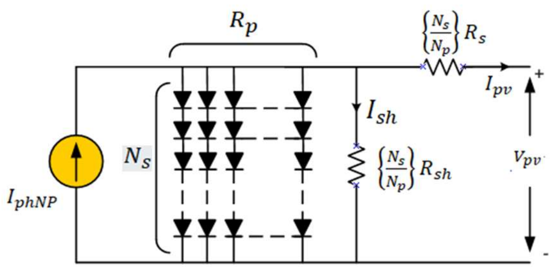

Figure 2: PV Array Circuits Equivalent

$$I_{PV} = I_{ph}N_p - I_r N_p \left[exp\left(\frac{q\left(V_{pv} + R_s\left(\frac{N_s}{N_p}\right)I_{pv}\right)}{N_s kT\alpha} \right) - 1 \right] - \frac{V_{pv} + R_s\left(\frac{N_s}{N_p}\right)I_{pv}}{R_{sh}\left(\frac{N_s}{N_p}\right)} \quad (8)$$

N_s is the number of PV modules installed in series, and N_p is the number of PV modules installed in parallel. While I_{pv} is the PV output current, and V_{pv} is the PV output voltage.

In this study, the type of the solar panel used is a monocrystalline type, Greentek MSP-100W. The detailed specifications of this product is shown in table 1.

Table 1: Electrical specification of PV MSP-100W [21]

No	Parameters	Variable	Value
1	Maximum power	P_{max}	100 W
2	Voltage at P_{max}	V_{mp}	18.1 V
3	Current at P_{max}	I_{mp}	5.54A
4	Open circuit voltage	V_{oc}	22.2V
5	Short-circuit current	I_{sc}	6.00A
6	Temperature coefficient of V_{oc}	K_v	-(0.40 ± 0.05)%/^{0}C
7	Temperature coefficient of I_{sc}	K_i	(0.065 ± 0.01)%/^{0}C
8	No. of cells and connection	n_s	72 (4 x 18)

The current and voltage characteristics of the MSP-100W PV module with various levels of solar radiation under constant operating temperature conditions is presented in Figure 3. Meanwhile Figure 4 shows the current and voltage characteristics of the MSP-100W PV module at constant radiation and variable temperature.

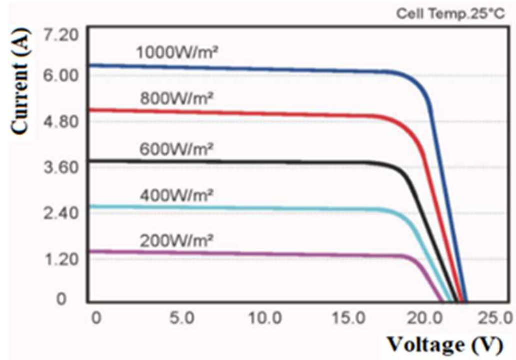

Figure 3: I-V Curves of PV Module MSP-100W [21]

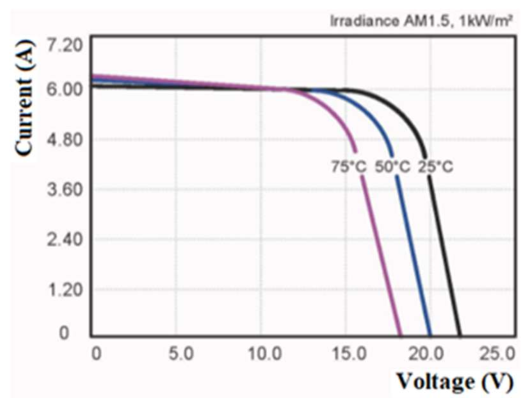

Figure 4: I-V Curves of PV Modules MSP-100W at Various Cell Temperatures [21]

1.4. Dual Axis Solar Tracker

The main objective of the research is to optimize electrical energy from solar panels by minimizing the angle of incidence of solar radiation on the solar panels' surface. The surface of the solar panel must be perpendicular to the incoming solar radiation in order for it to be perpendicular to the surface of the solar panel. As a result, even though the sun's position is changing all the time, the sun position tracker must be able to retain the angle of incidence of solar radiation with the surface of the solar panel as small as possible. The position of the sun in the sky can be determined by two angles, the elevation angle and the azimuth angle, as shown in Figure 5 [22][23].

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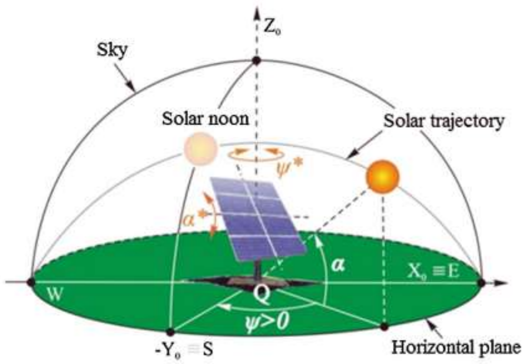

Figure 5: Azimuth And Altitude Angle [23]

The azimuth axis is perpendicular to the ground, and the altitude axis is perpendicular to it. To determine the magnitude of the altitude angle (α), use equation (9) and equation (10) to determine the azimuth angle [24].

$$\alpha = \arcsin(\sin\delta \sin\Phi + \cos\delta \cos\omega \cos\Phi) \quad (9)$$

$$A = 180^0 + sign(sin\ \omega)\ x\ arccos\left(\frac{\sin\alpha \sin\Phi - sin\ \delta}{cos\alpha\ cos\Phi}\right) \quad (10)$$

Where A is the azimuth angle, δ is the equator's latitude angle with the sun, Φ is the local latitude, and ω is the solar hour angle, which is 0 when the sun is at its highest position for one day.

2. PROPOSED SYSTEMS

Several steps are involved in the construction of the dual-axis solar tracker to ensure that the research is accurately designed and executed. It begins by designing the system's block diagram consisting of hardware components used to construct the proposed system as shown in Figure 6. The whole working algorithms are summed up in the flowcharts shown in the 7. In addition, the hardware design construction is presented in Figure 8.

The dual-axis solar tracker system has been designed and developed with main components are four LDRs as sensors, an Arduino Mega 2560 as a control processor, a four channel relay module, and two linear actuators. The block diagram of this system is presented in Figure 6. The position of the solar panel surface is moved in the direction of the highest intensity of sunlight based on the difference in intensity value. This is the direction of movement of the solar panel surface for the east, west, north, and south positions based on the intensity of sunlight measured by the LDRs sensors, which analogizes the movement of the X axis and Y axis or what is known as a double axis tracker. The LDR's output is an analog signal, which is connected to the analog pin on the Arduino Mega 2560. The data is then processed according to the programming algorithm, which results in an instruction for the actuator to move. The actuator movement corresponds to the intensity difference obtained from the LDR sensors.

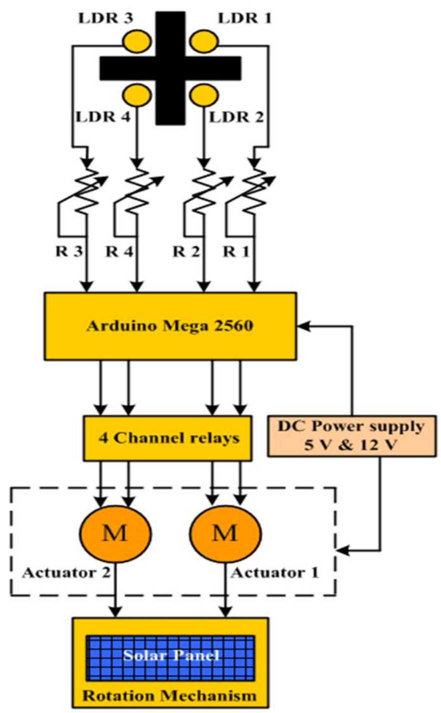

Figure 6: The Proposed System's Block Diagram

Furthermore, the mechanical position and surface of the solar panel move to find a position perpendicular to the sun's light direction. To operate the Arduino Mega 2560 and actuators, however, an additional DC voltage source is required. The workflow of the dual-axis solar position tracking system is depicted in Figure 7.

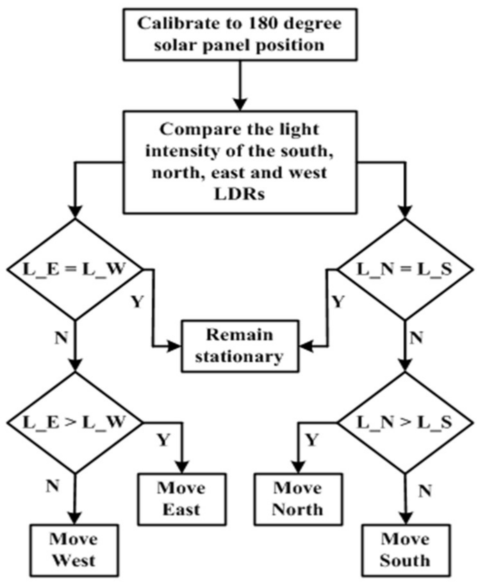

Figure 7: Workflow of a Solar Position Tracking System Using a Dual Axis

Calibration process is carried out at the beginning so that the solar panels are in horizontal position (180 degrees). The system is activated and the LDR sensor starts working to measure the sun's intensity if it is in the proper position. The LDR is divided into two parts, oone for where the first axis (X axis) is located for east and west directions and the other two for where the second axis (Y axis) is located for north and south directions. If the LDR for the east direction detects a value of the sun's intensity greater than the west or other positions, the actuator will move the mechanical system and the surface of the solar panel towards the east, and vice versa. However, if the solar intensity detected by the LDR for the east and west positions is the same, the solar panel will be in a stationary position, which usually occurs among 11 AM and 12 PM. The work process that occurs in the LDR for the east and west positions also applies to the north and south position processes.

The structure of the dual axis solar position tracking system is straightforward but efficient. The main support pole is made of iron and can support the weight of the load from the solar panels, while the actuators used are calibrated to the weight of the existing load. In this study, two hydraulic linear actuators of the Harl-3618 type with a maximum load capacity of 250 Kg and smooth movement are used.

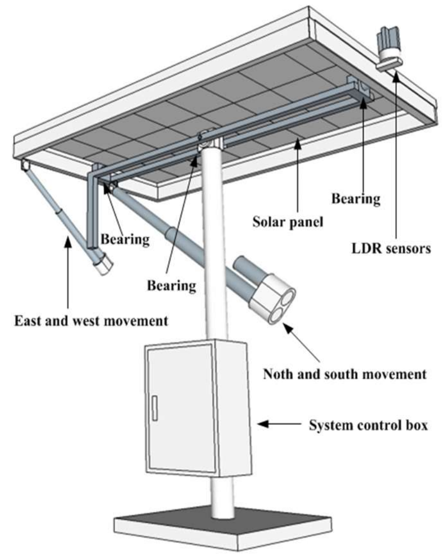

Figure 8: Design of a Solar Position Tracking System Using Dual Axis

Figure 8 depicts the design of the dual-axis construction of the sun position tracking system with a dual axis that able to move on the X and Y axes using two linear actuators.

3. RESULT AND ANALYSIS

The dual-axis sun position monitoring system's hardware construction and testing are conducted when the design phase is complete. The system is tested under three distinct weather conditions: a sunny day, a sunny day with clouds, and a cloudy day with rain. This test is carried out to evaluate and compare the performance of the solar position tracking system employing a dual axis in an effort to generate electrical energy under varying weather conditions. In addition, the same test procedure is also applied to the solar panel that uses a fixed system. Those varying weather conditions are taken into account in order to determine whether the dual-axis solar tracker keeps producing electrical energy. The electrical parameter data such as voltage, current, and power output are recorded during the test using the Parallax Data Acquisition (PLX-DAQ) interface as depicted in Figure 9.

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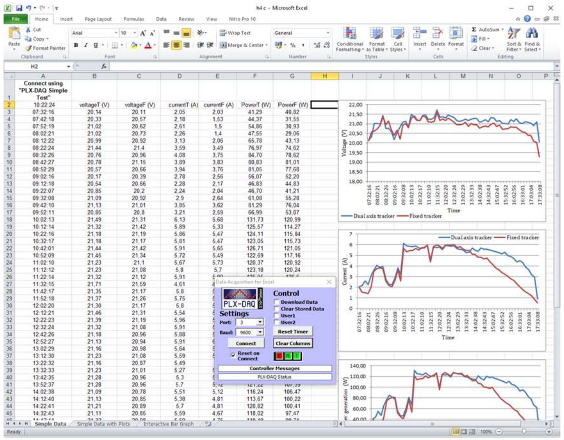

Figure 9: Interface Using PLX-DAQ

Installation of solar panels with a fixed tracker system and a dual-axis tracker system for testing can be seen in Figure 10. Furthermore, the comparison of voltage, current, and power output between the comparison of a fixed tracker system and a dual axis tracker system under three different weather conditions are presented in Figures 11 to 19. According to the test results, the dual-axis solar tracker produces more energy than the system with a fixed system in all weather conditions. However, the pattern of energy produced on a cloudy day with rain differs slightly from the other two weather conditions.

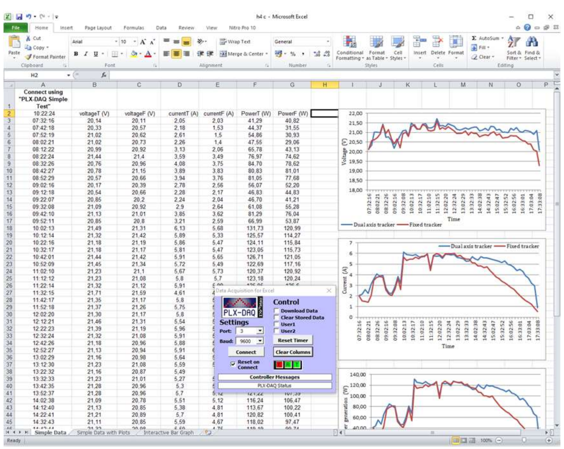

Figure 9: Interface Using PLX-DAQ

Installation of solar panels with a fixed tracker system and a dual axis tracker system for testing can be seen in Figure 10.

Figure 10: System Testing

Figure 11 shows the result of testing done from morning to evening on the first day under sunny conditions. The output voltage (V_{oc}) ranges from 20 to 22 volts from the beginning to the end of the test. However, the output voltage remains stable at 21 volts. The voltage value generated by the dual axis tracker system is always greater than the one produced by the fixed system. On average values, the voltage generated by the dual axis system and fixed system is 20.20 Volts and 20.81 Volts, respectively.

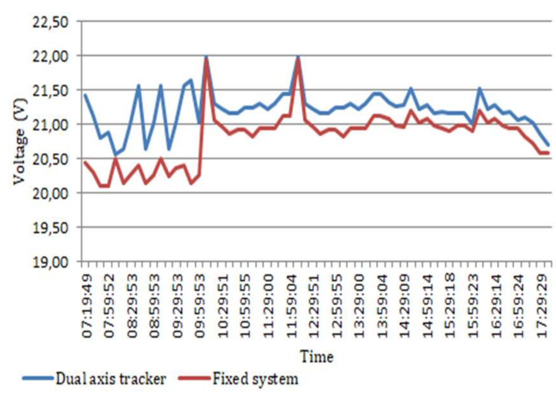

Figure 11: A Comparison of the Voltage Values Generated During the Sunny Day Test

The current characteristics (*Isc*) of the system during the test is shown in Figure 12. In the solar panels with a dual axis tracking system, the current tends to rise in the morning until 10 PM but after that the current is between 4 A to 6 A. However, in a solar panel with a fixed system, the resulting current has decreased from 12.30 AM until the end of the test. The average current of dual axis system and fixed system is 5.06 A and 4.38, respectively.

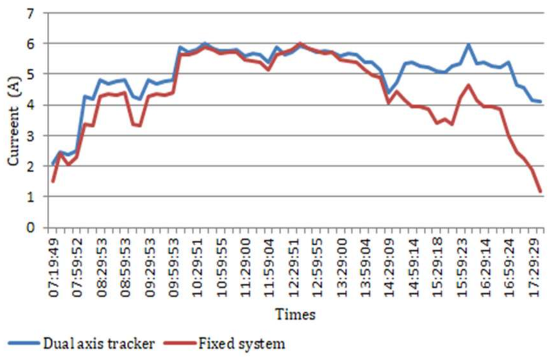

Figure 12: A Comparison of the Current Values Generated During the Sunny Day Test

Figure 13 shows the typical shape of the electrical energy generated in the first day's test. The pattern follows the current characteristics generated during the test. The difference in electrical energy produced using a dual axis tracking system is 17.5% higher than using a fixed system.

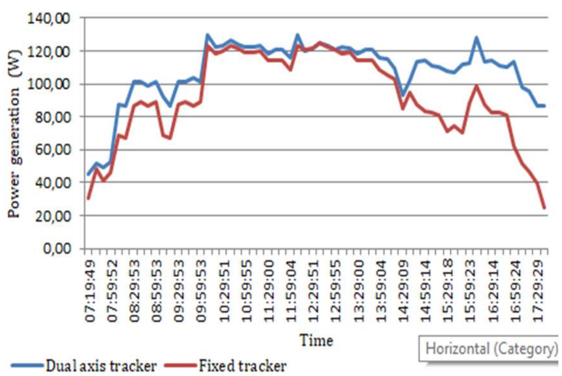

Figure 13: A Comparison of the Power Values Generated During the Sunny Day Test

Figures 14, 15, and 16 show the characteristics of the second test. The weather is cloudy in the morning and sunny around 10 PM, but there are more cloud shadows after 13:00 AM until the test is finished. The obtained voltage value is stable over 20 volts at the beginning of the test, but it rapidly drops after 17.00 AM as additional cloud shadows block the sun. The average voltage produced by a dual axis system and a fixed system is 21.09 Volt and 20.86, respectively.

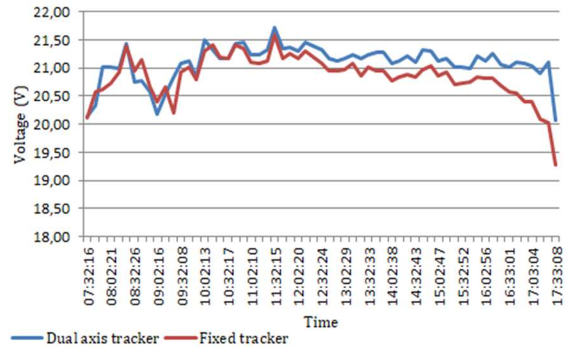

Figure 14: A Comparison of the Voltage Values Generated During the Cloudy Day Test

Figure 15 shows the characteristics of the current generated during the second test. The value of the current generated varied from the beginning of the test until 10 AM then it become stable until it sharply dropped after 12:30 AM. Solar panels with a dual axis tracker system, as opposed to solar panels with a fixed system, can still produce a greater current value even when there are many cloud shadows. With a dual axis system, the average test current is 4.66 A, but with a fixed system, it is 3.96 A.

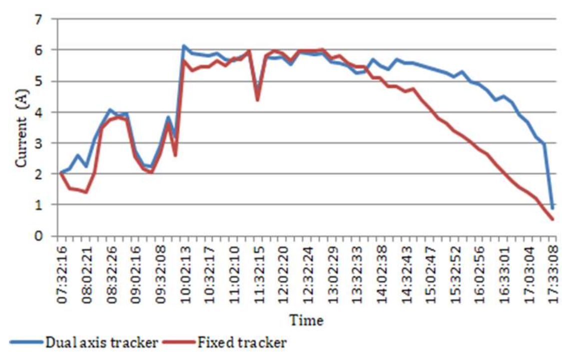

Figure 15: A Comparison of the Current Values Generated During the Cloudy Day Test

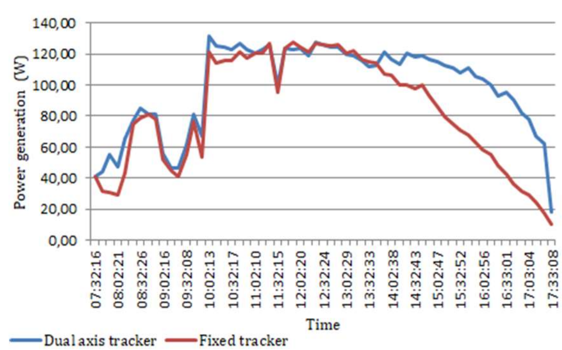

Figure 16: A Comparison of the Power Values Generated During the Cloudy Day Test

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The electrical energy generated in the second test remains the same as the resulting current pattern. Although there is a thick cloud shadow during the test on the second day, solar panels with a dual axis tracker system is able to produce 18.56% greater electrical energy than solar panels using a fixed system.

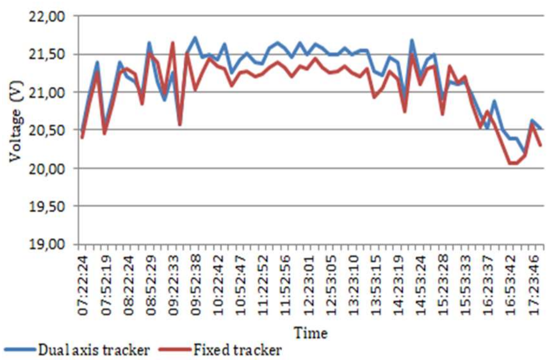

Figure 17: A Comparison of the Voltage Values Obtained When Testing Cloudy Day Interspersed With Rain

Figure 17, Figure 18, and Figure 19 show the results of the third test. The voltage is almost stable on solar panels using a dual axis tracker system which is above 20 Volts. Meanwhile, the current tends to increase from morning to midday, while there have been a few cases of a sharp fall because cloud shadows prevented sunlight from penetrating the solar panel's surface as shown in Figure 18. The current, however, dropped precipitously from 13.30 PM till the test's conclusion. The test will eventually come to a conclusion with a minor increase in the value of the resulting current because of the occurrence of dense cloud shadows and some light rain.

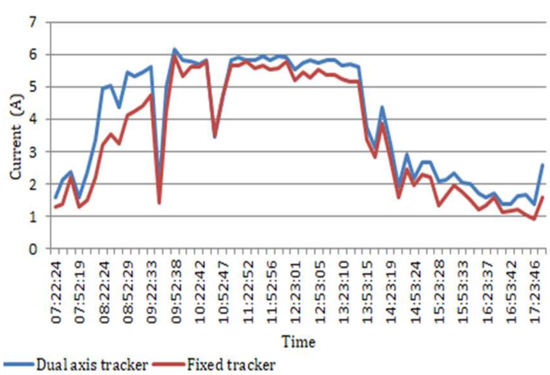

Figure 18: A Comparison of the Current Values Obtained When Testing Cloudy Day Interspersed With Rain

The pattern of electrical energy generated during the third test from morning to evening is depicted in Figure 19. During the test, the electrical energy generated by the system using the dual axis method is always greater in both voltage and current value than the solar panels using the fix system. The maximum electrical energy generated during the test occurred around 10:00 AM.

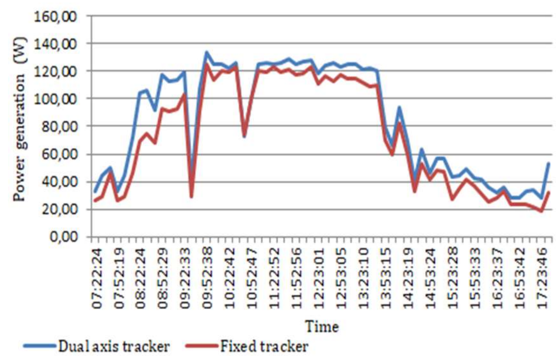

Figure 19: A Comparison of the Power Values Obtained When Testing Cloudy Day Interspersed With Rain

On the third day of testing, the average value of electrical energy produced by a dual axis tracker system was 14.3% greater than solar panels using a fixed system.

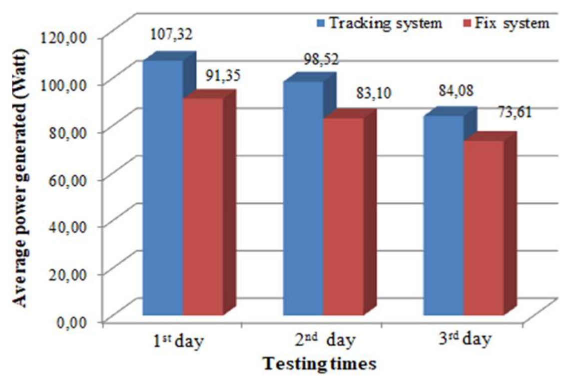

Figure 20: Average Electrical Energy Generated During the Test

Overall, the average electrical energy generated from testing with three different conditions can be seen in Figure 20. The comparative value of electrical energy generated by solar panels using a dual axis tracker system is always greater than that of solar panels using a fixed system. Thus, the system that has been built has proven to be successful in increasing the production of electrical energy despite changing environmental conditions such as sunny, cloudy and rainy weather conditions.

4. CONCLUSION

In comparison to a fixed system, the proposed design for solar position tracking uses a dual axis solar tracking system. From the test results, tracking the sun's position using a dual axis solar tracking system has better performance than a fixed system. The average electrical energy produced by the dual axis solar tracking system is greater than the fixed system in the first test by 17.5%, 18.56% in the second test, and 14.3% in the third test. During the test, the cloud's shadow has a strong influence on the system's ability to generate electrical energy. Thus, tracking the sun's position with a dual axis solar tracking system is more effective in increasing the production of electrical energy in photovoltaic systems. The results of the tests show that the dual axis solar tracking system is effective and efficient in increasing electrical energy production. Despite the fact that the components used are simple and inexpensive.

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