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A COMPARATIVE STUDY OF A DUAL-AXIS SOLAR TRACKING SYSTEM OVER A-FIXED-AXIS SOLAR PANEL USING FUZZY LOGIC CONTROLLER

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ABSTRACT

Photovoltaic (PV) energy provides advantages like low maintenance requirements and effectiveness in remote locations, while having a minimal environmental footprint. Nonetheless, the majority of PV systems are fixed flat-plate setups, which can lead to decreased energy production because of varying solar irradiation levels. The aim of this study is to evaluate the performance of a fuzzy controlled solar tracker system with dual axes compared to a fixed system. Fuzzy logic controllers are employed to regulate the motion of a dual-axis solar tracker system, enhancing the power output from the solar panels. The system utilizes a Mamdani fuzzy logic model, implemented through MATLAB Simulink, to interface with Arduino for controlling the system's movement. To evaluate the effectiveness of the proposed models, the power output of stationary photovoltaic panels is compared to the power output of fuzzy controlled dual-axis panels. The findings indicate that a solar tracker system with dual axes yields a 24.18% increase in power output.

KEYWORDS: Dual-axis solar tracker – Arduino MEGA2560 - fuzzy logic algorithm-Membership function

دراسة مقارنة لنظام تتبع شمسي ثنائي المحور مقارنةً بالألواح الشمسية الثابتة باستخدام وحدة تحكم منطق ضبابي.

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الملخص

تقدم الطاقة الكهروضوئية (PV) فوائد مثل انخفاض الصيانة والملاءمة للمناطق النائية، مع تأثير بيئي ضئيل. ومع ذلك، فإن معظم أنظمة الطاقة الشمسية الكهروضوئية هي تركيبات ثابتة ذات ألواح مسطحة، مما يؤدي إلى تقليل إنتاج الطاقة بسبب تذبذب الإشعاع الشمسي. هدف هذه الدراسة هو تقييم أداء أنظمة تتبع الطاقة الشمسية ذات المحورين التي يتم التحكم فيها بواسطة المنطق الضبابي مقارنةً بالنظام الثابت. تُستخدم وحدات التحكم المنطقية الضبابية لتنظيم حركة نظام تتبع شمسي ثنائي المحور، مما يعزز إنتاج الطاقة من الألواح الشمسية. يستخدم النظام نموذج منطق ضبابي من نوع (Mamdani)، يتم تنفيذه من خلال MATLAB Simulink، للاتصال مع Arduino للتحكم في حركة النظام. لتقييم فعالية النموذج ، يتم مقارنة ناتج الطاقة للألواح

الشمسية الثابتة بناتج الطاقة للألواح الشمسية ذات المحاور المزدوجة التي يتم التحكم فيها بواسطة المنطق الضبابي. تشير النتائج إلى أن نظام تتبع الطاقة الشمسية ذو المحورين يحقق زيادة بنسبة ٢٤،١٨٪ في إنتاج الطاقة.

الكلمات المفتاحية : متتبع شمسي ثنائي المحور ، Arduino MEGA2560 ، خوارزمية المنطق الضبابي ، دالة العضوية

1. INTRODUCTION

The world's energy consumption is gradually rising. Compared to developed nations, developing and undeveloped nations have a greater rise in energy consumption. Egypt produced 16,590 GWh of energy in December 2023 [1], with fossil fuels accounting for the majority of that total. Fossil fuel-based energy generation has numerous drawbacks, including increased pollution and environmental impacts, global warming, the depletion of finite fuel supplies, and the production of toxic gases that are bad for the environment and human health. These issues can be resolved by switching to renewable energy sources instead of fossil fuels. The integration of renewable energy sources (RE) significantly increases the key problems and impacts on current power networks. In addition to conventional energy sources, energy from renewable sources (RE) is gaining traction as a means of meeting the system's increasing demand for reliability and sustainable development. RE, in the form of distributed generation (DGs), is therefore widely used for electricity production from utility size generation to dispersed-scale projects due to its capacity to generate electrical energy without relying on fossil fuels. By 2050, it is anticipated that the amount of power produced worldwide from renewable sources will have increased to around 45 trillion kWh [2]. Renewable energy technologies are expanding quickly due to the urgent need to lessen reliance on fossil fuels and reduce carbon gas emissions from the production of power. The pressing issues posed by climate change are directly addressed by the quick development of renewable resources, underscoring the need for a shift to ecologically friendly and sustainable energy production techniques. In order to meet the growing need for power while reducing the negative effects on the environment, there has been a notable movement towards the utilization of wind, solar, hydro, and other sources of renewable energy[3]. With the world's energy resources being limited, photovoltaic (PV) energy emerges as a promising alternative for the future. [4]. Photovoltaic technologies have gained significant attention as an optimal energy source, primarily due to their environmentally friendly nature. These technologies generate electricity by harnessing the abundant energy provided by the sun, which is a readily available and free source of power. Once the necessary infrastructure is in place, photovoltaic systems operate without causing any pollution, making them an ideal choice for sustainable energy production.[5]. Because it is renewable, limitless, and non-polluting, photovoltaic energy has garnered a lot of interest among sources of renewable energy [6]. The efficiency of electrical energy generation from solar cells is influenced by many factors, including solar radiation intensity, ambient temperature, and cell efficiency. It is important to note that the higher the solar intensity, the greater the energy production.To optimize the quantity of solar radiation that reaches the earth's surface, it is crucial to track the position of the Sun and adjust the solar panels accordingly. By aligning the panels with the Sun's position, the maximum irradiation can be achieved, leading to increased energy production. There are several methods available for solar tracking, each falling into different categories based on their functionality. There are two basic categories of solar tracking methods: dual-axis and single-axis tracking, as well as passive and active tracking. A tracker system with a single-axis operates with one degree of freedom, allowing movement along one axis, typically left to right. On the other hand, a dual-axis solar tracker system offers two degrees of freedom, enabling movement both right to left and down to up. In order to power actuators, controllers, and electrical motors that track the position of the Sun, active solar trackers need an extra electrical power source.[7].

The design of an active, solar tracker system with a dual-axis using an Arduino MEGA 2560 and a light-dependent resistor (LDR) sensor is covered in this paper. The Arduino MEGA 2560 microcontroller, two stepper motors, four LDR sensors, and a solar plate were used to create this prototype tracker.

1.1. LITERATURE REVIEW

In 2015, Syafii, Refdinal Nazir, Kamshory, and Muhammad Hadi introduced sensor-free dual-axis solar trackers that utilize the sun's position and a database of sunrise and sunset times. By comparing power generation in an upright versus flat position, they found that the solar tracker increased energy storage by 225.05 Watthour, leading to a 26% improvement in solar power generation efficiency.[٨].

In a study by Hassan Fathabadi in 2016, it was demonstrated that the proposed solar tracking system accurately follows the sun's path with a minimal tracking error of 0.11°, outperforming both sensor-based and sensor-less solar trackers. The main advantage of implementing this solar tracking system is a significant enhancement in energy efficiency ranging from 28.8% to 43.6%, varying by season.[٩].

Amadi and Gutierrez's 2019 study assessed how well a solar tracking system with a dual-axis (DATS) provides reliable power for rural applications. A micro-controller, direct current (DC) motors, and (LDR) sensors were all part of the DATS. In addition to being cost-effective, the results showed that the DATS generated 67.9% more energy than fixed PV panel systems (FPPS) and 31.4% more energy than single-axis tracking systems.[10].

Zhu, Liu, and Yang (2020) presented a new design for a single-axis tracking system and evaluated its performance. By using geometric relationships and a solar radiation model, they derived mathematical equations for tracking. The proposed system demonstrated a significant reduction of 96.40% in annual solar radiation compared to a dual-axis system, surpassing single-axis structures at different latitudes.[١١].

In their bachelor's thesis, Mohd Said, Jumaat, and Anak Jawa (2020) compared single-axis and dual-axis solar tracker systems. The study findings indicated that the dual-axis system outperformed in capturing solar energy, resulting in higher current, voltage, and power outputs. Currently, the dual-axis system achieves an efficiency of 45.11%, highlighting its superior performance in energy generation.[١٢].

Ömer Gönül, Fatih Yazar, A. Can Duman, and Önder Güler (2022) found that solar trackers with a dual-axis provide the most boost in power generation as compared to fixed-tilt systems, ranging from 30.4% to 34.6%. However, they also have the longest payback period, ranging from 16.7 to 24 years. The most feasible method was found to be a monthly manual tilt adjustment, which increased electricity generation by 3.6–5% while reducing the fixed-tilt systems' payback period from 9.6 to 12.6 years by around 8 months.[١٣].

This paper concentrates on the ability of stepper motor and LDRs electronics and the capability of the MATLAB Simulink to control the dual-axis solar tracker system.

2. THEORETICAL ANALYSIS

On a hypothetical axis, the earth rotates once a day. Both the north and south poles are traversed by this axis. Perpendicular to this imaginary axis is the line known as the equator. The earth takes 365 days to complete its orbit around the sun, although it is tilted roughly 23.50 degrees off the line perpendicular to the plane of its orbit. The several axes of the planet are depicted in Figure 1 below.

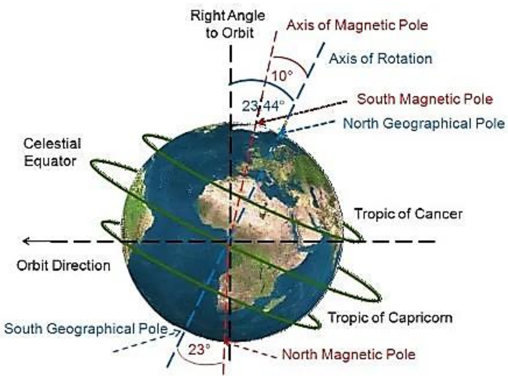

Fig. 1. Earth's Axis [14]

A. As seen in Figure 2, a location's latitude is the angle formed by the line connecting it to the earth's center and the equatorial plane.
B. Longitude The great semicircles along the surface of the earth joining the north to the south poles are called lines of longitude.
C. Zenith Angle of the Sun The line pointing to the sun and the vertical axis form this angle. This angle is 90 degrees at sunrise and dusk.
D. Angle of Solar Altitude This is the angle formed by the horizontal axis and the line pointing towards the sun. It is a zenith angle's complement. It is zero degrees at both ends of the day.
E. Azimuth Angle of the Sun The angle between the line pointing south and the line pointing to the sun is this. To the east, angles are negative. Positive angles are found to the west. At noon on the sun, this angle is zero.

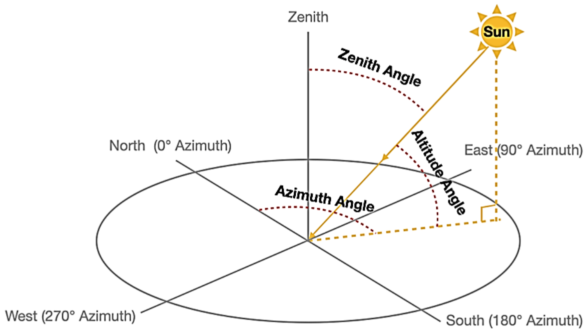

Fig. 2. Solar Zenith Angle, Solar Altitude Angle and Solar Azimuth Angle [15]

The sun's curved trajectory throughout the day or season is known as the "solar path." As is well known, the Earth revolves on both its axis and its orbit around the sun. This makes this path for each season or day. Figure 3 below depicts the solar path for a certain day on July 1, 3, and 5, 2024, in the geographical location of the 6th October city, Cairo (Latitude +29.956 North, Longitude +30.913 East, Altitude 192.3). An algorithm that is encoded in the Arduino platform can be created for this. Only for a specific day and location as specified, this algorithm aids in determining the elevation and azimuth angle for the solar panel orientation.

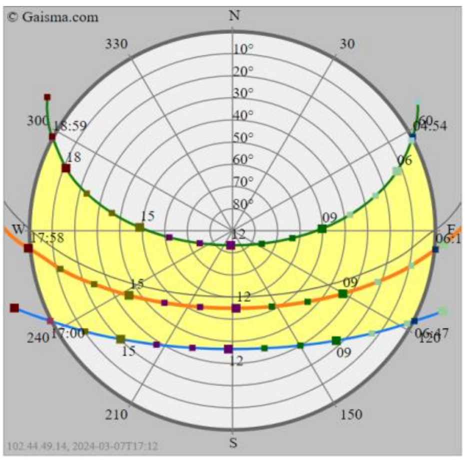

Fig. 3. The Solar trajectory of Cairo, Egypt. [16]

3. DESIGN AND CONSTRUCTION

With two degrees of freedom, a solar tracker system with dual axes can move in both horizontal and vertical planes at the same time.Table1, shows the hardware component and quantites utilized in the proposed solar tracker system

Two stepper motors make up a solar tracker system with dual axes. Each motor has one axis and is mounted in a certain place to move the plate about this axis as shown in Figure 4. It is rotated in a horizontal plane by the stepper motor in the first portion and a vertical plane by the stepper motor in the second.Table2,show the solar panel specifications utilized in proposed system.

Galvanized steel ASTM A37 Steel (t=2 mm) is used to make the frame. To create a frame, every component is dismantled and welded together. Additionally, each bearing is set up in a specific holder. A solar panel shaft is inserted into these bearing holes. To move this solar panel assembly, a gear system connects the stepper motor. This motor spins the solar panel in the appropriate direction upon receiving the control signal.

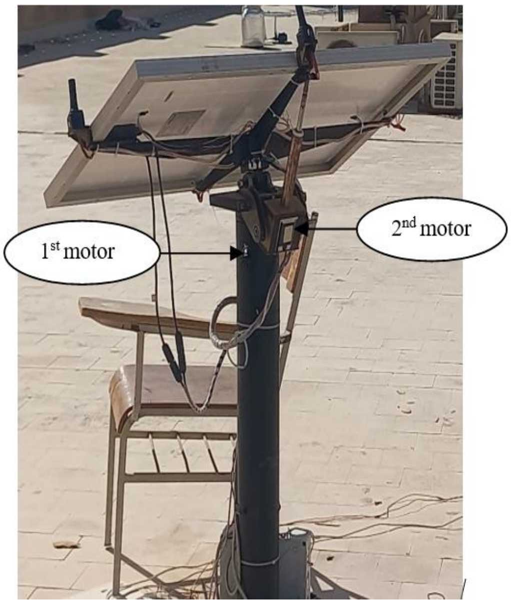

Fig. 4. Actual solar tracker system with dual axes

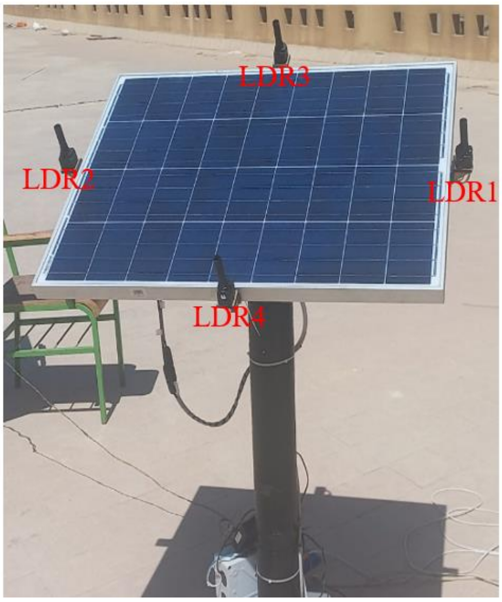

Fig. 5. Actual Locations of LDRs

Table 1: Hardware Parts List

Hardware Parts	Quantity
Arduino MEGA 2560	1
Solar panel, 80W	1
Stepper motor	2
100-Watt load Resistor 4.7 Ohm	2
LDR	4

Table 2: Solar Panel Specifications

Open Circuit Voltage	$V_{oc} = 21.96$ V
Short circuit current	$I_{sc} = 4.69$ A
Maximum Power	$P_{max} = 80$ W
No. of cells in parallel	$N_{pm} = 36$
No. of cells in series	$N_{sm} = 2$

4. METHODOLOGY AND ALGORITHM FOR PROPOSED SOLAR TRACKER SYSTEM

The dual-axis active solar tracker operates by using four LDR sensors positioned on the right,left, top, and bottom of the solar panel as seen in Figure 5. These sensors detect the intensity of sunlight, causing the resistance of the LDRs to change accordingly. After that, the Arduino Mega receives the resistance values to compare. By comparing the readings of the right and left LDRs, the first stepper motor is controlled to rotate the solar panel either clockwise or anticlockwise .

In the same way, the bottom and top LDR readings are compared to control the motion of the second stepper motor, either clockwise or anticlockwise. The solar panel rotates upward while the second motor is moving clockwise, and downward when it is moving anticlockwise. Based on the variation in LDR resistances, the microcontroller sends the relevant commands to the motor and determines its proper direction. Prior to the second motor, the first motor runs.

The LDRs continuously detect the location of the sun, allowing the solar panel to adjust until it reaches a perpendicular angle to maximize power generation. This cycle repeats until the panel stabilizes and remains in optimal position to capture sunlight efficiently.

The diagram in Figure 6 shows a dual-axis solar tracker system.

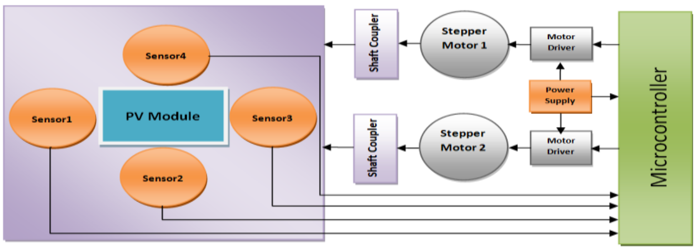

Fig. 6. Block Diagram of Dual-Axis Solar Tracker

The flowchart depicted in Figure 7 illustrates the algorithm utilized in the proposed tracking system for the sunlight position.

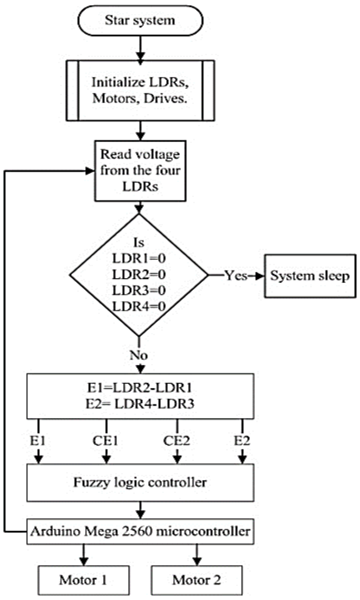

Fig. 7. Algorithm Flowchart for Solar Tracking.

5. FUZZY LOGIC CONTROLLER

The proposed system utilizes the error and the change in error from LDRs readings as inputs for fuzzy logic to regulate the movement of the tracking system. LDR1 and LDR2 are employed to adjust the first motor around the vertical axis, while LDR3 and LDR4 are responsible for controlling the second motor along the horizontal axis.

Triangle membership functions serve to characterize both inputs and outputs. As illustrated in Figure 8, 9 the universe of discourse for each input comprises six distinct membership functions.

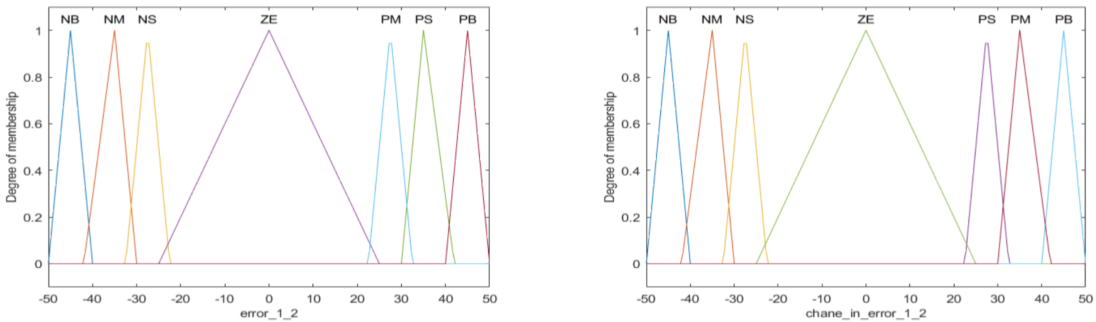

Fig. 8. Membership Function of Error and Change of Error of LDR1 and LDR2

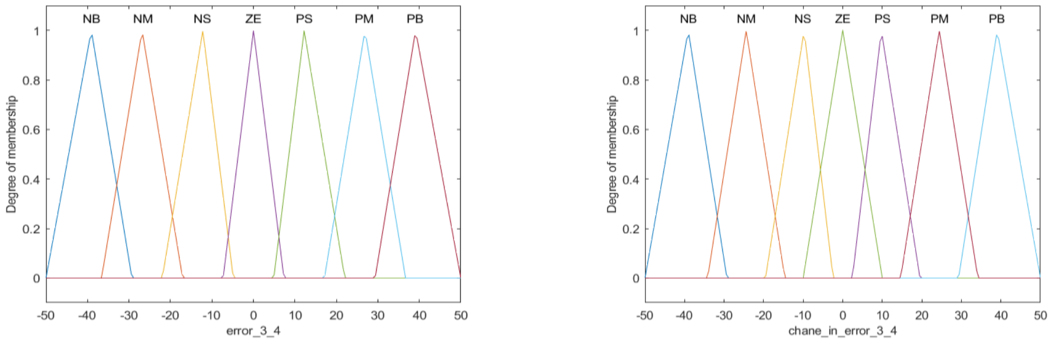

Fig. 9. Membership Function of Error and Change of Error of LDR3 and LDR4

Each output dictates the movement of the first and second motors. Figure 10,11 This illustrates the discourse universe for each output, featuring six triangular membership functions.

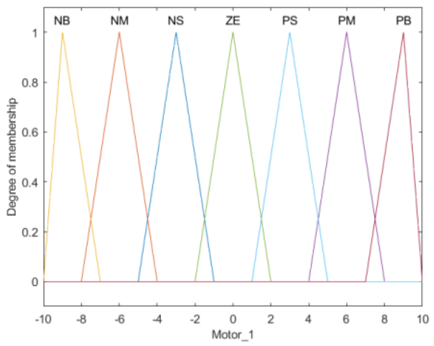

Fig. 10. Membership Function of First Motor Motion

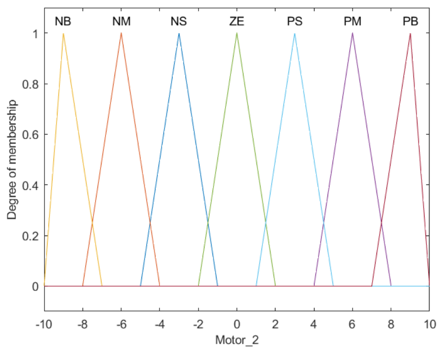

Fig. 11. Membership Function of Second Motor Motion

The fuzzy rules presented in Table V illustrate the relationship between the error and the change in error readings from LDRs, which are utilized to determine the movement of the two motors.

Table 3: Fuzzy Rule Related to The Inputs and Outputs

CE / E	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

6. RESULTS AND DISCUSSION

The voltage, current, and power readings from the photovoltaic (PV) module are being recorded on

Data	1,3,5 -July- 2024
Location	Latitude +29.956 North, Longitude +30.913 East, Altitude 192.3m
Sunrise	06:01 AM,
Sunset	08:00 PM,08:01 PM, 08:01 PM

The graph displayed in Figure 12 illustrates the relationship between the average output current in Ampere and the time in hours, for both the fixed-axis solar panel and fuzzy controlled dual-axis solar tracker.

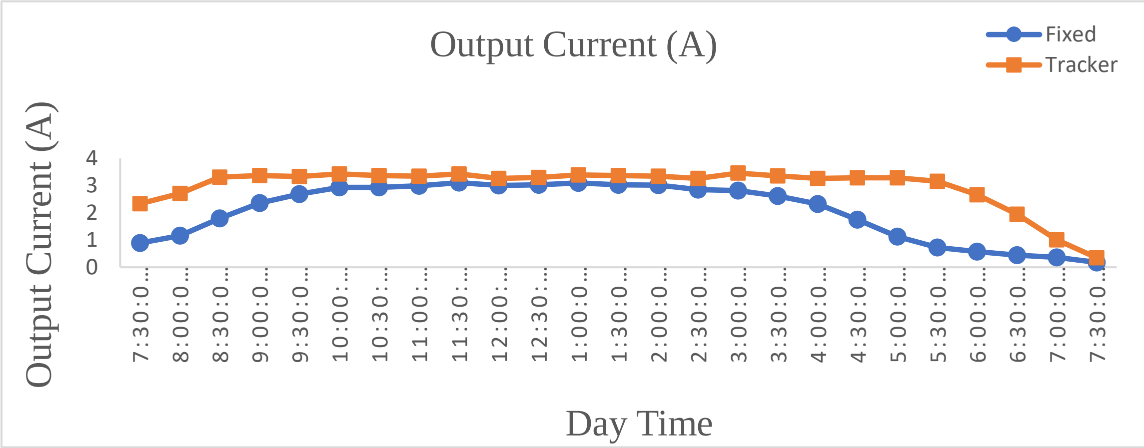

Fig. 12. Output Current (A) vs. Day Time (Hours)

The graph of the fuzzy controlled solar tracker system with dual-axis and fixed-axis solar panels is displayed in Figure 13 below. It is plotted against the average output voltage (V) and the time (hr).

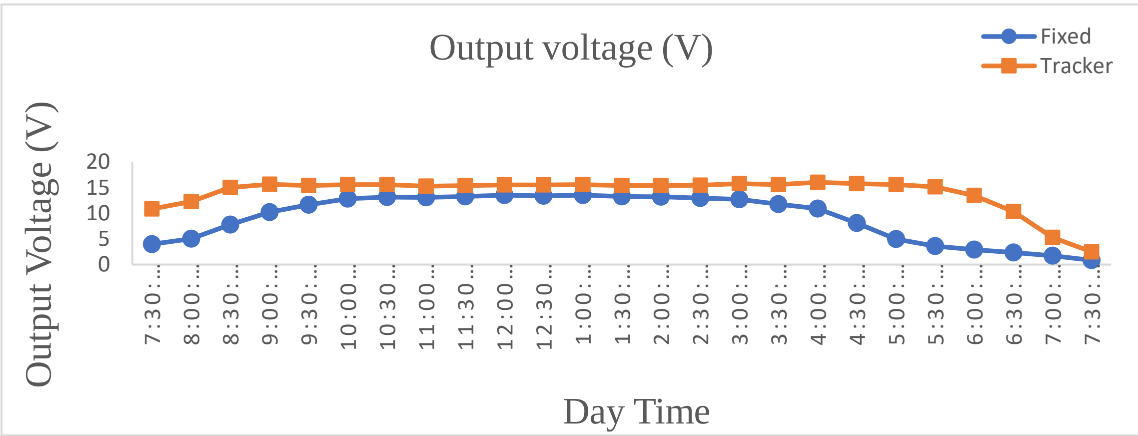

Fig. 13.Output Voltage (V) vs. Day Time (Hours)

The graph of the fuzzy controlled solar tracker system with dual-axis and fixed-axis solar panel is displayed in Figure 14 below. It is plotted against the time (hr) and the average output power in (W).

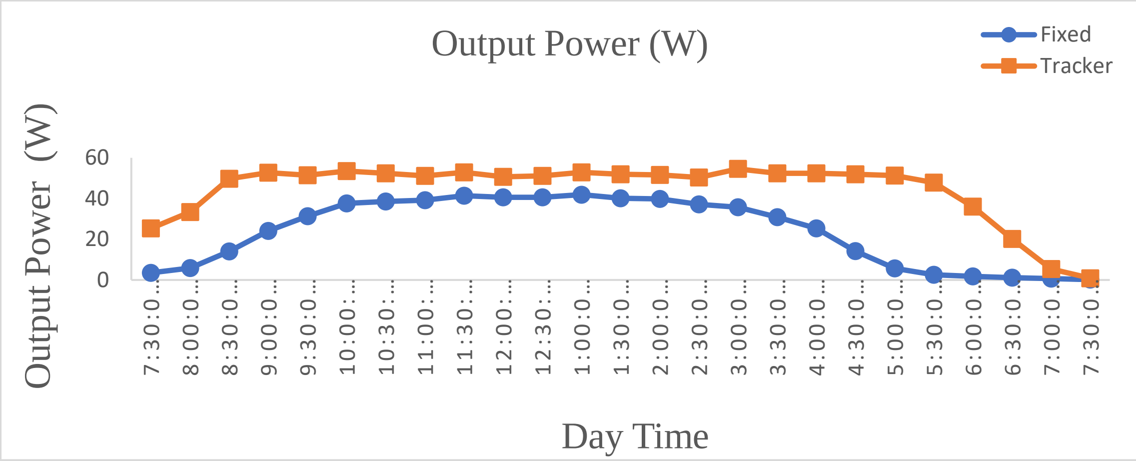

Fig. 14. Output Power (W) vs. Day Time (Hours)

The comparison of output current, voltage, and power between fixed axis and fuzzy controlled dual-axis solar tracker is illustrated in Figures 12, 13, and 14. Upon analyzing these figures, it becomes evident that the fuzzy-controlled dual-axis tracker outperforms the fixed-axis tracker in terms of efficiency and overall performance. The data presented in the figures clearly indicates that the fuzzy-controlled dual-axis tracker is superior to the fixed-axis tracker, making it the better choice for solar energy generation.
Figure 14 clearly shows that the fuzzy controlled dual-axis solar tracker outperforms the fixed-axis solar tracker. For example, at 07:30 AM, the fixed axis PV module generates 3.55 W, while the dual-axis tracker PV module produces a much higher 25.36 W when connected to a 4.7-ohm power load resistor. The main advantage of the dual-axis solar tracker is its ability to generate higher output power during specific time intervals, such as from 07:30 AM to 9:00 AM and 04:30 PM to 06:30 PM. Although there is no significant difference in output power during peak hours, the dual-axis solar tracker consistently produces maximum power, with the highest output power recorded at 54.53W for the same load.

Between 7:30 AM and 7:30 PM, the fuzzy-controlled dual-axis tracker system yields an average power gain of 85.82% over the stationary solar panel. This demonstrates how well the tracker system works to maximize energy output throughout the day and shows a notable improvement in power generation when compared to a fixed solar panel arrangement.

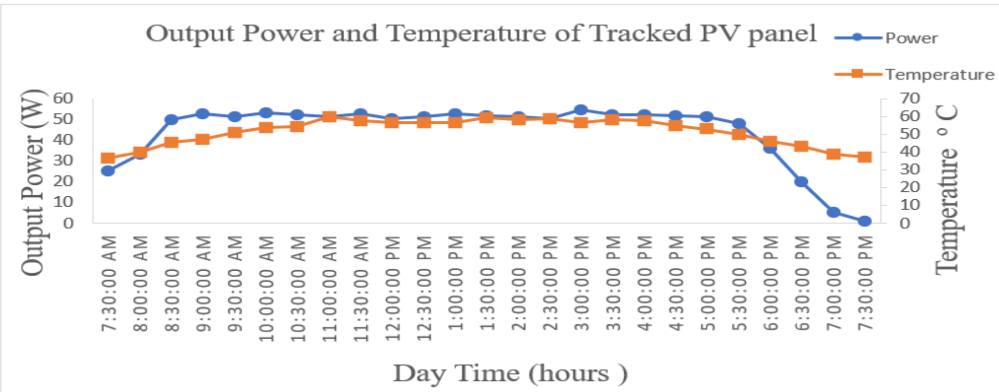

Fig. 15. Output Power and Temperature of Tracked PV Panel

Figure 15 depicts the temperature and output power of the dual-axis tracker system during the daytime.

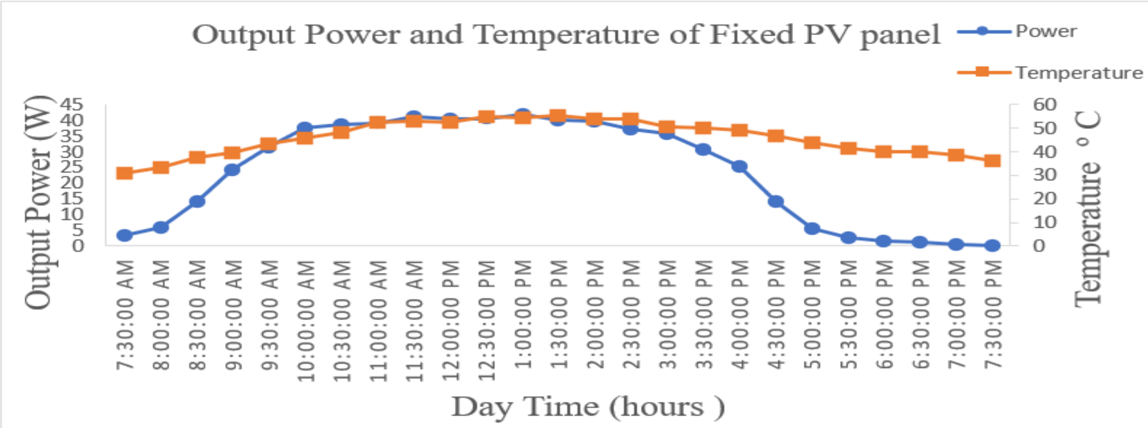

Fig. 16. Output Power and Temperature of Fixed PV Panel

Figure 16 illustrates the temperature and output power of the stationary photovoltaic panel throughout the daytime.

CONCLUSION

The fuzzy controlled solar tracking system with a dual axis underwent design, construction, and testing across different conditions, with its efficiency being determined based on these varying circumstances. The final design test results revealed a significant 85.82% enhancement in comparison to the fixed solar panels utilized for reference, showcasing the system's impressive performance. Notably, the net power gained from the system amounted to 24.18.%

The stepper motor operates continuously, drawing power throughout its operation. However, there are certain times of the day when the energy generated by the dual-axis tracking system is lower than the energy consumed. To maximize efficiency, it is recommended to utilize the dual-axis tracking system during specific periods and then halt its operation. For instance, using the dual-axis solar tracker from 07:30 AM to 06:30 PM can result in a power gain of 28.23% compared to a solar panel with fixed.

The efficiency of a photovoltaic (PV) module in a dual tracker system may be adversely affected by an increase in temperature, resulting in a decline in performance. To improve the overall performance of the solar tracking system with a dual axis and maximize the power output from the PV module that tracks the sun's movement, it is recommended to incorporate a cooling system in future developments. This will help to mitigate the adverse effect of temperature on the PV module and ensure consistent and optimal performance.

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