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Design and Implementation of Single Axis Solar Tracking System: Utilizing GPS, Astronomical Equations, and Satellite Dish Actuator for Optimal Efficiency

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ABSTRACT

Globally, the focus is on maximizing the energy yield and efficiency of PV systems as an essential renewable energy source. Different methods have been proposed to achieve this goal. Where the sun's location in the sky is changed during the day, a tracking mechanism has been proposed as a promising technology to harness the maximum amount of solar radiation by PV system as compared to the fixed panels. In this study, the design and implementation of a polar single-axis tracking system is presented to improve the energy efficiency of PV system through angular variation during the day using the proposed tracking system. This is achieved by interconnecting some devices that include GPS sensors and satellite dish actuators as the main components that are managed and controlled using astronomical equations. The designed system is tracked in a discrete manner that can be adjusted automatically during the day related to each degree change of azimuth angle of the sun from sunrise to sunset. The system has been field tested in Sulaymaniyah, Iraq, to evaluate its performance in different weather conditions and compare it with a fixed PV system. The test results for the clear sky indicated that the increased amount of energy production for the tracking system is 36.6% as compared with the stationary panel. Whereas, for a mostly cloudy day the measured amount of increase was 18.5%. This improvement of the harnessed energy for PV systems is important to make the system more efficient and sustainable.

Keywords: Solar tracking, Astronomical equations, Satellite dish actuator, Renewable energy.

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1. INTRODUCTION

At the time, renewable energy is wildly focused worldwide to replace fossil fuel-based energy resources. The solar PV system is one of the promising technologies to sustain this transition. However, the optimal efficiency of these PV systems remains a persistent challenge. The performance characteristics of a photovoltaic (PV) panel are influenced by more than just solar irradiance, weather conditions, and ambient temperature; they are also notably affected by the angle at which solar radiation strikes the PV panel's surface.

During the day, the location of the sun with respect to Earth changes from east to west leading to a continuous change of the incident beam angle of the sun on the PV panel **(Chua et al., 2017)**. As a result, the power density on a fixed PV panel is varied throughout the day where the received radiation beam on PV panel is proportional to the cosine of the angle of the incident **(Al-Najjar, 2023)**. Different techniques have been proposed to maximize the extracted amount of energy of the sun by PV panels. Utilizing technologies with improved energy efficiency, modifying the ratio between the capacity and inverter of the panels, and cooling the surface of the panels are three main approaches to increase the efficiency of PV power plants **(Kerekes et al., 2011; Stropnik and Stritih, 2016; Elibol et al., 2017)**. Although these techniques will support PV panels to gain more energy, the fixed structures are the primary factor of PV systems' low efficiency **(Carvalho et al., 2013)**. Therefore, one other promising way to improve energy capture is through solar tracking technology **(Koussa et al., 2012; Kashan and Al-Qrimli, 2020; AL-Khateeb and Sinjari, 2023)**, which moves PV panels to follow the movement of the sun through the day to have a perpendicular incident angle.

Based on the flexibility of their movements, single-axis and dual-axis systems are the two main categories of solar tracking technology **(Thi Hoa et al., 2022)**. Single-axis systems are simple and economical, tracking either the sun's east-west or north-south path. In contrast, dual-axis systems, though more complex, expensive while control both angle adjustments for increased efficiency **(Mavromatakis and Franghiadakis, 2008; Seme et al., 2011; Seme and Štumberger, 2011; Hafez et al., 2018)**. Since double-axis PV tracking systems only provide a slight increase in energy yield over single-axis tracking systems, there are situations in which investing in them may not be financially practical **(Seme et al., 2020)**. For more accurate sun tracking, these systems can be managed by closed-loop, sensor-based techniques or open-loop where it is less accurate algorithms **(Awasthi et al., 2020)**. Electrical motors and sensors are used by active solar tracking systems to guarantee exact alignment with the sun's position. In contrast, gas-filled canisters used in passive systems are less precise because of temperature changes **(Nsengiyumva et al., 2018).**

There are some strategies to promote the use of solar energy, including solar systems that are capable of tracking the sun's movement as an efficient technique. The system autonomously aligns itself with the sun's movement, ensuring that the incoming sunlight always strikes the PV panel's surface at a perfect right angle. This adjustment significantly enhances collection efficiency, resulting in a 10-100% increase **(Mousazadeh et al., 2009)**, where the extent of improvement depends on factors such as the tracking mechanism, control system, local weather, and location conditions **(Lazaroiu et al., 2015)**. Solar trackers come in various types, as mentioned they are determined by their method of following the Sun's path, either along a single axis or a dual axis. Typically, these systems predominantly rely on microcontrollers, employing a range of methods to track the Sun's position. These methods encompass the utilization of electro-optical sensors or GPS coupled with astronomical equations **(Mousazadeh et al., 2009; Salas et al., 2010)**. The two main methods of adjusting the orientation of solar panels to follow the sun's path are continuous and discontinuous tracking **(De Sá Campos and Tiba, 2021)**. The first one involves continuously adjusting the position of solar panels to keep them pointed directly at the sun as it moves across the sky throughout the day. The later also known as incremental tracking, involves adjusting the orientation of solar panels at specific intervals during the day or a season. Certainly, here is an overview of some of the studies conducted in this field, as outlined below.

In Malaysia, a single-axis solar tracking system was developed and field-tested, incorporating a PIC microcontroller and an electro-optical sensor. On clear days, the system substantially increased the average power output, by approximately 66.92%, for the time before 11:00 AM and after 3:00 PM when compared to the fixed panel **(Mahendran et al., 2013)**. However, its effectiveness decreased in other weather conditions. A cost-effective and adaptable solar tracker was also implemented using a low-cost PIC 16F microcontroller and photo sensors. This system outperforms stationary panels by capturing maximum solar energy throughout the day which demonstrates a 40% improvement in efficiency compared to fixed panels **(Abu Sneineh and Salah, 2019)**. Another research presents a two-axis solar tracker integrated with a motorized satellite dish for precise sun tracking. It uses an LDR sensor to measure sunlight intensity, and the system proves to be over 35% more efficient than fixed solar panels **(Mustafa et al., 2018)**. Notably, the energy gain is highest in the morning and evening, with minimal difference at noon, highlighting the fixed panels' effectiveness during midday **(Mahendran et al., 2013)**. Although the system with LDR sensors operates with a high degree of accuracy **(Ghazali and Abdul Rahman, 2012; Sumathi et al., 2017)**, it struggles with adverse weather conditions, such as cloud cover, leading to inaccuracies.

An experimental study was conducted in Jordan for a period of one year for two systems with 7.98 kWp each, based on the recorded data to compare their performance the actual generated energy of the tracker system is 31.29% higher as compared to the stationary PV system **(Hammad et al., 2017)**. In the locations where PV panels are surrounded by tall buildings and other reflected materials, different sources of light, namely direct and diffuse, are in place, which causes unstable operation of the sensor-based trackers. Therefore, this type of tracker mechanism requires precise design, installation, and alliance **(Thi Hoa et al., 2022)**.

In Baghdad, Iraq, experimental research was conducted on the design of a global dual-axis solar tracking system that relies on GPS accompanied by astronomical equations. The research objective is to propose a solution to the concerns raised by the tracking systems that use optical sensors. **(Al-Naima et al., 2014)**. Moreover, a comparative study has been conducted to compare a prototype sensor-based tracking system with a stationary PV panel. The measured data for the test system at clear sky indicated that the amount of energy gain is 57% as compared to the fixed panel where the data were recorded every 15 minutes (**Al-Haddad and Hassan, 2011)**. An experimental study was conducted in Kirkuk, Iraq, to assess a designed single-axis horizontal discrete system. Astronomical equations were used to calculate the azimuth angle of the sun based on the latitude and longitude of the location. During the test, the tracking system is moved nine times per day in a regular pattern. From the results, it can be said that the amount of collected energy with the tracking system can be increased by approximately 17% **(Mohammed and Mohammed, 2022)**. Finally, a comparative experimental test has been conducted for a period of one year to assess the performance of a discrete solar PV tracker and stationary PV panel at various weather

conditions. The outcomes of this test indicated that the PV system with a tracker system performs better at all conditions of weather including rain and cloud **(Kuttybay et al., 2020)**.
Overall, numerous research studies have been conducted worldwide to design and assess the performance of tracking systems; different strategies are proposed and tested, either practical or simulation-based. Most of the systems were sensor-based, and others used GPS and astronomical equations to overcome the issues related to the accuracy of photoelectrical sensor-based trackers. The amount of radiation that reaches the PV panel surface highly depends on the geographical location, weather, and time of the day **(Şenpinar and Cebeci, 2012; Filik and Filik, 2017; Hafez et al., 2018)**. Therefore, researches were carried out in Iraq, where there are limited experimental studies on the tracking system for different weather conditions, and most of the systems were photoelectrically sensor-based. Based on the knowledge of the researchers there is no conducted research in this field in Sulaymaniyah. Therefore, this research is conducted to design, implement, and perform an assessment of a mobile single-axis tracking system that can be used anywhere in the world to accurately track the sun's position using GPS and astronomical equations. Then, it is field tested in Sulaymaniyah, Iraq in different weather conditions, and its performance is compared with a stationary PV system. For the purpose of assessment, the data for each system is recorded every second using a data logger to get a precise result and significant evaluation.

2. THEORY OF TRACKING

The astronomical equations are used for the purpose of azimuth angle calculation. This can be used to perform decision making and accordingly controlling the tracking mechanism. There are different ways to express astronomical equations, each with various level of precision. The two most important formulas that have been used to monitor the sun's position in the sky are the Declination Angle (DA) and the Equation of Time (EoT) (**Iqbal, 1983; Kalogirou, 2014; Al-Naima et al., 2014)**.

2.1 Declination Angle (DA)

The solar declination angle describes the angular displacement of the sun's rays with respect to the equator. It is positive when the ray's movement is toward the north (**Kalogirou, 2014)**. The declination angle in degrees for any given day of the year can be accurately calculated using the following seven-term Fourier expansion. This approach provides a precise, efficient, and mathematically robust representation of DA annual variation (**Duffie and Beckman, 2008)**.

$$DA = 57.296\,[0.006918 - 0.399912\cos(y) + 0.070257\sin(y) - 0.006758\cos(2y) + 0.000907\sin(2y) - 0.002697\cos(3y) + 0.001480\sin(3y)] \quad (1)$$

Where y is the day angle (radian) and n is the day of the year.

$$y = \frac{1}{365}[2\pi(n-1)] \quad (2)$$

2.2 Equation of Time (EoT)

For longitude correction, the difference between the time displayed on a clock and the time indicated by the position of the sun must be determined. The method described below can be used to compute this correction. The values of EoT in minutes, as a function of the day of the year, can be accurately determined using the first five terms of the Fourier expansion.

$$EoT = 229.18[0.000075 + 0.001868\,cos(y) - 0.032077\,sin(y) - 0.014615\,cos(2y) - 0.04089\,sin(2y)] \quad (3)$$

2.3 Hour Angle (HA)

The hour angle HA is the angle that the Earth must rotate to position the meridian of a specific point directly under the sun **(Eldin et al., 2016)** This angle plays an important role in determining the position of the sun in the sky relative to a specific location on Earth. It also helps calculate the solar azimuth angle (the direction of the sun relative to the north). It also defines the time of day based on the sun's movement across the sky. The hour angle is zero at local solar noon, and each 0.25° of longitude (360° divided by (24x60)) equals 1 minute, with afternoon hours being positive. The hour angle in degrees is given by **(Kalogirou, 2014)**.

$$HA = \pm 0.25(\,No.of\ minuts\ from\ Ln) \quad (4)$$

The corrected local noon is calculated as **(Al-Naima et al., 2014):**

$$Ln = 12{:}00 - \frac{EoT(minuets)}{60} \quad (5)$$

2.4 Sunrise and Sunset Time

The time between sunrise and local solar noon is known as HSR, while the time between sunrise and sunset is HSS. The sunrise and sunset times are SRT and SST, respectively, and local solar noon is Ln. The sunrise and sunset time can be calculated as follows **(Al-Naima et al., 2014).**

$$HSS = -HSR = \frac{cos^{-1}(-tan(Latitude)tan(DA))}{15} \quad (6)$$

$$SRT = Ln - HSR \quad (7)$$

$$SST = Ln + HSS \quad (8)$$

2.5 Azimuth Angle (AA)

To collect the maximum amount of solar radiation it is required to move the solar panel to be aligned with the sun's rays. The solar azimuth angle is defined as the angle between the sun's rays and a line that is parallel to either the south or the north **(Mahmoud et al., 2023)**. This angle is fundamental for tracking the sun's position on the horizontal plane, ensuring that solar systems capture the maximum amount of energy throughout the day. This can be utilized for decision-making and subsequently controlling the tracking mechanism. This angle can be calculated using the below **Eq. (10)** depending on some parameters including solar altitude angle, declination angle, and solar hour angle **(Kuttybay et al., 2020)**. The Sun Altitude (SA) in the sky is calculated as:

$$SA = sin^{-1}\,(sin\,(DA)\ sin\ (Latitude)\ + cos\,(DA) cos\,(Latitude)\ cos\,(HA)\,) \quad (9)$$

Therefore, the Azimuth Angle (AA) can be calculated as:

$$AA = sin^{-1}\left(\frac{sin\,(DA)\,sin\,(Latitude) + cos\,(DA) cos\,(Latitude)\ cos\,(HA)}{cos\,(SA)}\right) \quad (10)$$

3. TRACKING SYSTEM DESIGN

3.1 Control System Design

The experimental system that has been proposed in this study is a polar single-axis discrete tracker that records the sun's movement from east to west throughout the day. The latitude of the test location is used to determine the fixed inclination of the system. An important measurement for tracking is the azimuth angle, which must be measured continually during the day. In order to accomplish this, several components have been used, namely a GPS sensor, an RTC unit, and a satellite dish actuator. The GPS sensor ensures monitoring of the geographical coordinates, date and time of the location. Besides the GPS is used to initialize the tracking system automatically in terms of date and time for any location on the earth, therefore this makes the system is mobile and can be used anywhere on the earth just by adjusting the tilt angle for the new location.
RTC unit is used to timekeeping continuously. It can also be used as a backup for the GPS device in the case of losing signal or when the GPS unit is in sleep mode or turned off for the purpose of energy conservation. A DC motor of the satellite dish actuator is also used to actuate the PV panel to ensure azimuth angle adjustment. Finally, the ATmega328P microcontroller collects position data, time and date from the GPS, and setting the RTC accordingly. The ATmega328P is embedded in the Arduino UNO board and is programmed using C++ through the Arduino IDE. After receiving time, date, and location data from peripheral devices, the microcontroller uses astronomical formulae to calculate the sun's azimuth angle. When the azimuth angle is set, the electric motor is activated to align the panel with the appropriate angle. Since the RTC and GPS devices both use the I2C and USART Serial communication protocols, respectively, the ATmega328P was chosen to support them. **Fig. 1** shows the suggested tracking system as a block design. It includes the microprocessor, GPS, actuator, and real-time clock (RTC). **Fig. 2** depicts the tracking system's controller components.

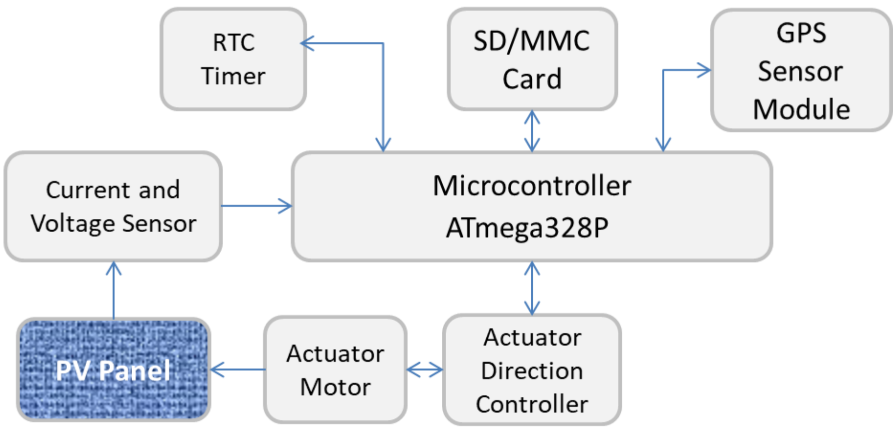

Figure 1. Block diagram for the proposed tracking system.

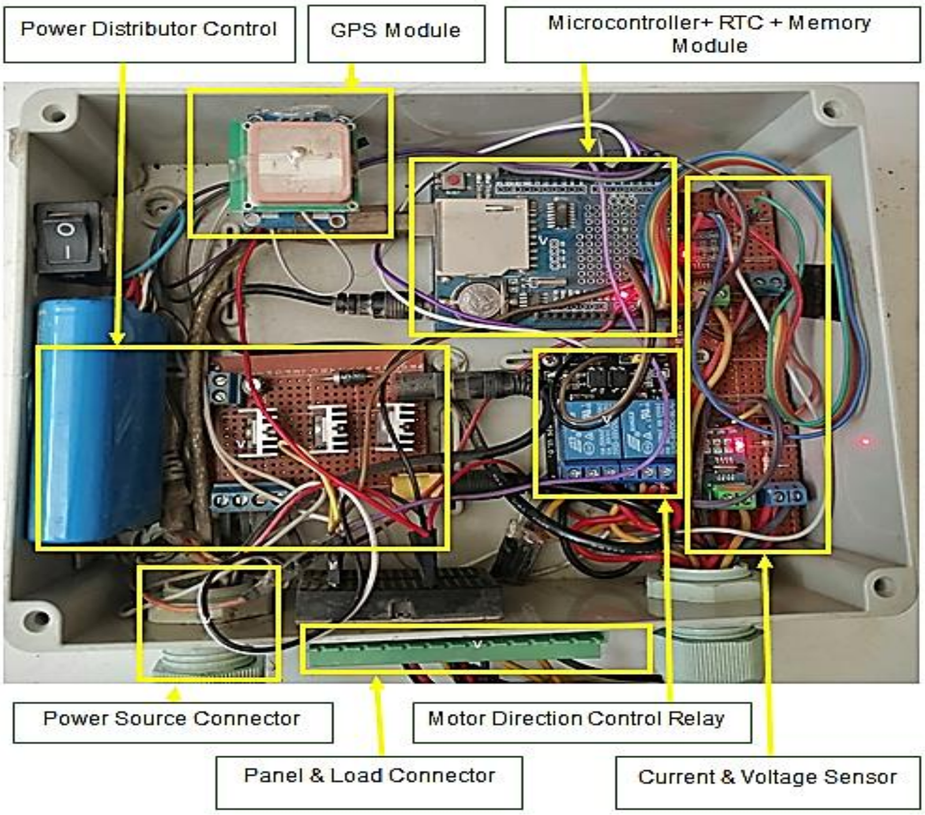

Figure 2. Controller components of the proposed tracking system.

3.2 Tracking System Algorithm

In the proposed system, the sun tracking algorithm makes it possible to precisely find the sun's azimuth angle and figure out the exact times of solar noon, sunrise, and sunset. During the setup process, the tracking system instantly initializes to start from the default position, which is east. The GPS then begins to gather time and position information. After recording the information, the microcontroller turns off the GPS once the real-time clock (RTC) synchronizes with it to preserve power and guarantee continuous and accurate timekeeping. The system then uses GPS data along with astronomical formulas to determine the sun's orientation angle. Subsequently, the orientation of the photovoltaic (PV) system is modified by controlling the actuator based on the measured azimuth angle. This algorithm enables the solar tracker to closely follow the sun's path, ensuring that the deviation in the azimuth angle remains within a one-degree range during daylight hours. The tilt angle is set to match the latitude of the installation location. A feedback signal from the actuator is received to verify the correct movement of the system. The system also checks sunrise and sunset times. Therefore, during the day, the azimuth motion control adjusts the panel by rotating it in a clockwise direction. However, at sunset time the panel is rotated back to the default position and the system enters a power-saving sleep mode to reduce energy consumption. The flowchart of the tracking system algorithm is shown in **Fig. 3**.

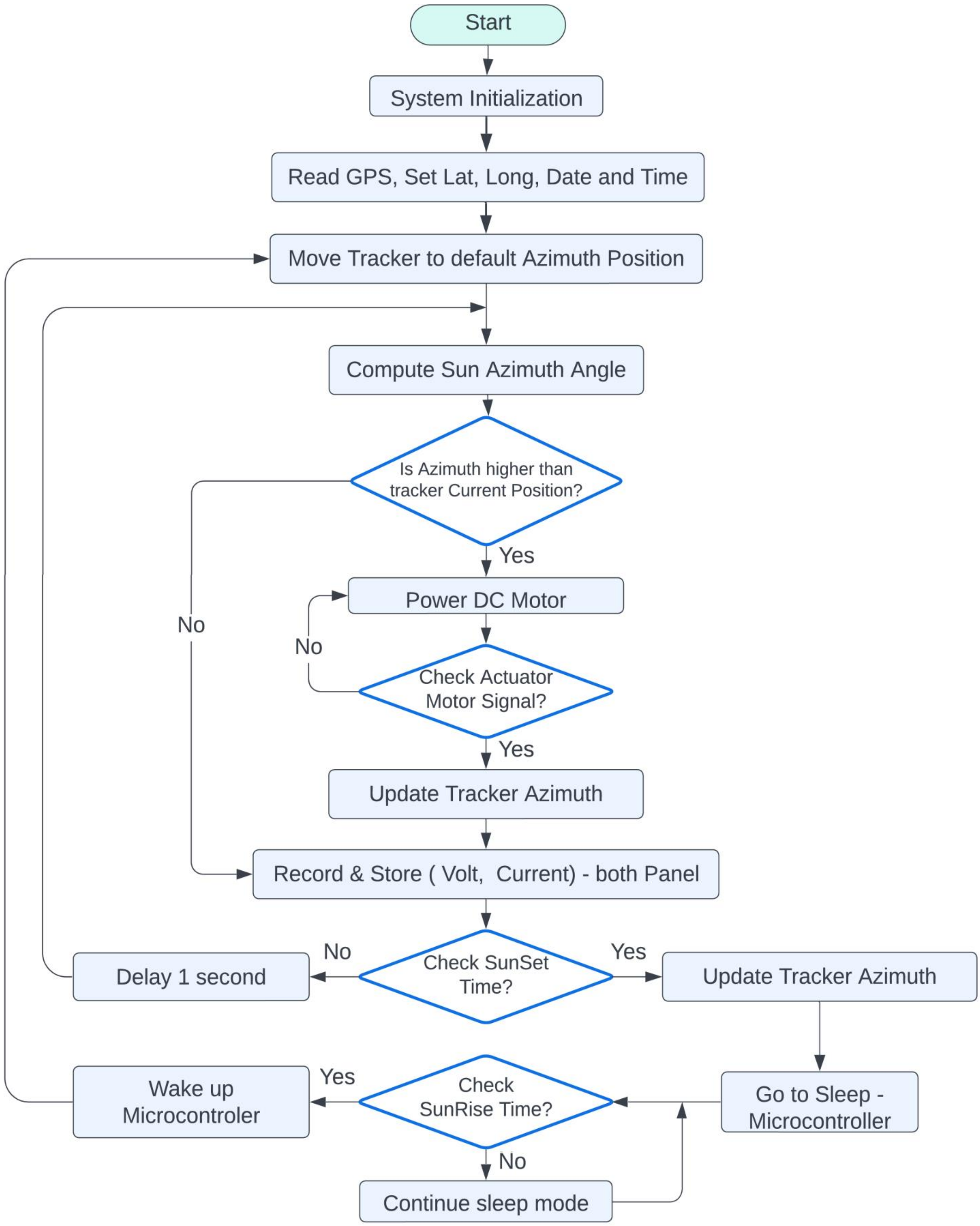

Figure 3. Flowchart of the tracking system algorithm.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experiment was carried out in Sulaymaniyah/ Iraq with 35.5558° N, and 45.4351° E latitude and longitude respectively. For the test system, two PV panels with the same property are used. One system is installed on a fixed metallic structure, and the other is installed on a structure equipped with a single-axis polar solar tracker as illustrated in **Fig. 4**. The metallic structure is designed in such a way to rotate around the axis of east-west. The tilt angle for both systems is 35° as the latitude. Each scheme consists of a PV source (with a given characteristic table shown in **Table 1** and a DC halogen light bulb as a load to be able to measure the current and voltage of the systems. Tests were conducted on various weather conditions, during which voltage and current data were collected through the use of voltage and current sensors.

Afternoon (South West)	Noon (South)	Morning (South East)

Figure 4. Fixed and Tracking PV Test Systems.

Table 1. Characteristics of the PV panels used.

All the Electrical Data are at STC	
Peak Power (P_{max})	100 W
Open Circuit Voltage (Voc)	21.7 V
Short Circuit Current (Isc)	6.57 A
Maximum Power Voltage (V_{max})	18 V
Maximum Power Current (I_{max})	5.56 A
Maximum System Voltage	1000 V
Power Tolerance	$\pm 3\%$

The study evaluates the solar tracker system's performance by measuring the power output of a tracking PV system and comparing it to a stationary PV. Continuous power data is recorded every second from sunrise to sunset, as depicted in the following graphs.

Figs. 5 to 7 depict the daily variations in power output from the PV panel for the tracking and stationary systems. The result from **Fig. 5** reveals that, on mostly clear days, the PV panel with a sun tracker generated 36.6% more energy as compared to the stationary system. Additionally, on partially cloudy days, as shown in **Fig. 6**, the tracking system outperformed the fixed-tilted PV system by about 34.9%. This indicates the tracking system's ability to adjust its orientation and maintain a more consistent energy yield, even in the presence of intermittent cloud cover. The result for a cloudy day in **Fig. 7** shows that both systems have the same pattern during midday as there was a cloud; the power gain with this weather condition for the test day was 18.5%. This is demonstrating its capability to generate more energy relative to the fixed system, although to a lesser extent than on clearer days. Moreover, it is important to note that the tracking system showed considerable differences in power generation during early morning and late evening hours, when the angle of sunlight varies significantly. In contrast, the fixed-tilted system experienced limitations during these times, resulting in reduced energy capture.

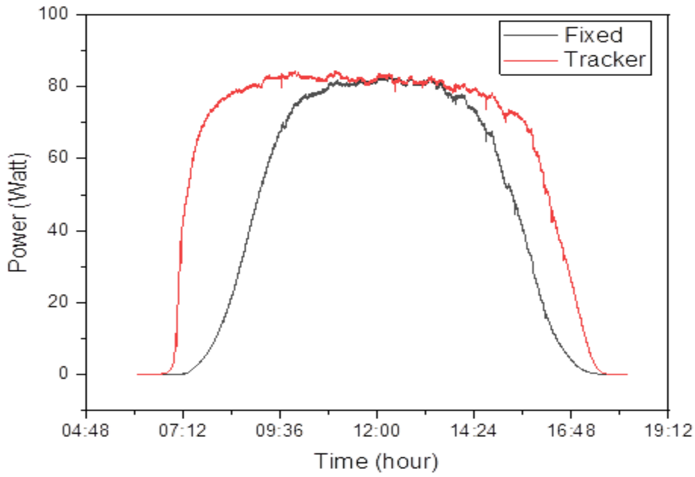

Figure 5. Output Power versus Time on Fixed and Tracking Systems on the 24th Sep. 2023.

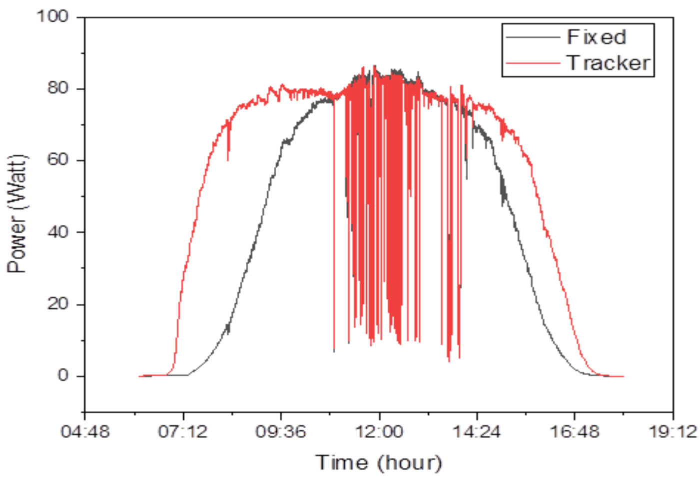

Figure 6. Output Power versus Time on Fixed and Tracking Systems on the 25th Sep. 2023.

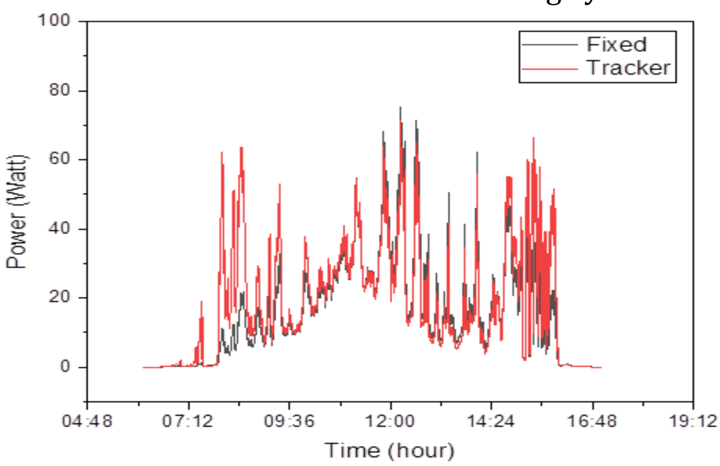

Figure 7. Output Power versus Time on Fixed and Tracking Systems on 1st October 2023.

Both the tracking and non-tracking systems presented a consistent trend of decreased power generation under cloudy conditions, as sunlight obstacle directly affects total energy output. Understanding this relationship between cloud cover and energy production is crucial for assessing the potential limitations of solar systems in varying weather conditions. Additionally, **Table 2** provides a complete overview of the total energy produced on the specified days, facilitating a thorough analysis of performance metrics. The tracker rate, as indicated in the table, quantifies the additional energy generated by the sun-tracking system, clearly illustrating its advantages over the fixed solar PV system across different environmental conditions.

Table 2. Summary of comparing fixed and tracking PV systems.

Day	Day Condition	Total Generated Energy (Wh/day)		Performance
		Fixed	Tracker	Tracker rate
24/09/2023	Clear Sky	535.57	731.81	36.6%
25/09/2023	Partly Cloudy	472	637	34.9%
1/10/2023	Mostly Cloudy	171	202	18.5%

5. CONCLUSIONS

Given the increasing significance of solar energy as a primary future energy source, this article presents a concise and clear overview of a solar tracking mechanism designed to enhance solar energy yield. The study focuses on the design and implementation of a mobile single-axis solar tracker utilizing a motorized satellite dish to accurately follow the sun's movement. The system incorporates GPS technology alongside astronomical equations to precisely determine the sun's position in the sky and can be used anywhere in the world. Comparative analysis reveals the effectiveness of the solar tracking system over fixed solar panels. Despite overcoming the challenges related to photoelectric sensors the energy harvested from the proposed single-axis tracker amounts to 36.6% more than that obtained from fixed solar panels for a clear sky day. Data analysis further indicates that the solar tracker performs optimally during morning and evening periods for the tested location, highlighting its enhanced efficiency compared to fixed solar panels, which are most effective only during noon.

NOMENCLATURE

Symbol	Description	Symbol	Description
AA	Azimuth Angle, deg.	Ln	Local solar noon, hr
DA	Declination Angle, deg.	LDR	Light Dependent Resistor
EoT	Equation of Time, min	PV	Photovoltaic
GPS	Global Positioning System	RTC	Real Time Clock
HA	Hour Angle, deg.	SA	Sun Altitude, deg.
HSR	Period from sunset to noon, hr	SRT	Sun Rise Time, hr
HSS	Period between noon and sunset, hr	SST	Sun Set Time, hr

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Credit Authorship Contribution Statement

Rizgar Ahmed Salih: Writing – review & editing, Writing – original draft, Validation, Hardware Implementation, Software, Methodology. Karzan Qadir Mohammed: Writing – review & editing, Writing – original draft, Validation. Peshawa Osman Hama: Writing – review & editing. Rawaz Othman Hassan: Writing – review & editing. Barham Kamal Noori: Hardware Implementation, Software, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تصميم وتنفيذ نظام تتبع الطاقة الشمسية أحادي المحور: استخدام نظام GPS والمعادلات الفلكية ومشغل أطباق الأقمار الصناعية لتحقيق الكفاءة المثلى

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الخلاصة

على الصعيد العالمي، ينصب التركيز على تعظيم إنتاج الطاقة وكفاءة أنظمة الطاقة الكهروضوئية كمصدر أساسي للطاقة المتجددة. وقد تم اقتراح طرق مختلفة لتحقيق هذا الهدف. حيث تم اقتراح آلية تتبع كتكنولوجيا واعدة لتسخير أقصى قدر من الإشعاع الشمسي بواسطة نظام الطاقة الكهروضوئية مقارنة بالألواح الثابتة عندما يتغير موقع الشمس في السماء أثناء النهار. في هذه الدراسة، تم تقديم تصميم وتنفيذ نظام تتبع أحادي المحور قطبي لتحسين كفاءة الطاقة لنظام الطاقة الكهروضوئية من خلال التباين الزاوي أثناء النهار باستخدام نظام التتبع المقترح. يتم تحقيق ذلك من خلال ربط بعض الأجهزة التي تتضمن أجهزة استشعار GPS ومشغلات أطباق الأقمار الصناعية كمكونات رئيسية يتم إدارتها والتحكم فيها باستخدام المعادلات الفلكية. يتم تتبع النظام المصمم بطريقة منفصلة يمكن تعديلها تلقائيًا أثناء النهار فيما يتعلق بكل درجة تغير في زاوية سمت الشمس من شروق الشمس إلى غروبها. تم اختبار النظام ميدانيًا في السليمانية بالعراق لتقييم أدائه في ظروف الطقس المختلفة ومقارنته بنظام الطاقة الكهروضوئية الثابتة. أشارت نتائج الاختبار للسماء الصافية إلى أن الزيادة في كمية الطاقة المنتجة لنظام التتبع بلغت 36.6% مقارنة باللوحة الثابتة. في حين بلغت الزيادة المقاسة 18.5% في يوم غائم في الغالب. يعد هذا التحسن في الطاقة المستغلة لأنظمة الطاقة الكهروضوئية مهمًا لجعل النظام أكثر كفاءة واستدامة.

الكلمات المفتاحية: تتبع الطاقة الشمسية، المعادلات الفلكية، مشغل طبق القمر الصناعي، الطاقة المتجددة، الكفاءة المثلى.