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DESIGN OF A COMPLEX DUAL-AXIS SOLAR TRACKER WITH AN INTEGRATED SOLAR PV MONITORING SYSTEM

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The object of this study is two-axis tracker systems for tracking the position of the Sun and monitoring the parameters of photovoltaic panels. The task addressed is the optimization of photovoltaic panel positioning to improve their efficiency and maximize electricity generation, specifically selecting the optimal tracking algorithm while accounting for implementation cost and payback period under variable climatic conditions.

The essence of the results is the design and deployment of a system that controls panel tilt and azimuth angles according to the chosen tracking algorithm, while performing online monitoring of key photovoltaic converter operating parameters and meteorological data. By accurately calculating the Sun's trajectory and employing dual-axis tracking, the number of unnecessary movements is reduced, which lowers the tracker's energy consumption and drive wear, thereby improving system reliability and reducing operational costs.

These findings are associated with the use of dual-axis algorithms with precise solar-position calculations, as well as by the implementation of a web interface and an integrated database for collecting statistical data on tracking performance. The system provides real-time data collection and analysis, allowing the tracking algorithm to be changed and its effectiveness to be evaluated for a specific location or climatic zone. The user-friendly web interface enables users to access information in the form of plots and sensor readings.

In practice, the designed system can be used for long-term monitoring of tracking efficiency, to analyze return on investment, as well as plan operational expenditures. Experimental studies showed that the dual-axis tracker with a precise solar-position calculation algorithm increases energy generation efficiency on a spring sunny day in the western region of Ukraine by more than 25%

Keywords: dual-axis solar tracker, online monitoring system, web interface, solar cell, clean energy

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1. Introduction

The growing interest in the implementation of environmentally friendly technologies in industry stimulates an intensive search for solutions to increase the productivity of energy generation from renewable sources. Under today's conditions, when energy needs are growing and the challenges of climate change are intensifying, research in the field of photovoltaic systems is critically important for ensuring energy independence and reducing environmental impact.

Over the past decades, there has been an active development of photovoltaic [1] and thermoelectric [2, 3] energy converters. However, the main disadvantage of thermoelectric energy converters is the low efficiency, which, albeit slowly, is being increased every year [4]. One of the most promising areas of renewable energy is photovoltaic converters, which are capable of directly converting solar radiation into electrical energy. The use of these technologies opens up opportunities for the optimal use of natural resources and the creation of a stable, reliable energy infrastructure. This allows companies to not only optimize operating costs but also minimize their environmental impact, which is an important step towards sustainable development [5].

Photovoltaics are the leading renewable energy source, with the latest IRENA report predicting that by the end of 2024, the global share of photovoltaics would be 1,865 GW, with installed capacity increasing by 32.2% year-on-year [6]. One of the major challenges in using photovoltaics is their relatively low efficiency; for example, silicon photovoltaics, which are the most popular in the industry, have an efficiency of 20–25% under standard testing conditions [7].

A key factor affecting the performance of photovoltaics is the amount of solar radiation reaching the panel surface, which determines the number of photons involved in generating electricity. Ensuring that the angle of inclination of the panels corresponds to direct solar radiation is an important task, as it contributes to increasing the amount of current generation during the day. There are industrial tracking systems of various types, both with one axis of rotation and with two axes; they improve the efficiency of solar energy use but significantly increase the cost of the system and prolong the payback period. The effectiveness of the tracking system also significantly depends on the selected algorithm of operation.

The application of automatic positioning devices for photovoltaic cells is relevant for improving the efficiency of photovoltaic systems. Research aimed at designing a comprehensive system for assessing the effectiveness of tracking under actual conditions with a selected algorithm and online monitoring of the parameters of the photovoltaic converter and weather conditions is relevant for modern challenges.

2. Literature review and problem statement

In [8], the results of using a two-axis tracker for positioning the Upsolar UP-M250P solar panel are reported; the authors propose a scheme based on the Intel Edison module that controls the DFS10G-05 gearmotors according to the control algorithm based on the equations for determining the position of the Sun; as noted in the work, measurements were carried out from 9:00 to 16:00 and were recorded every 30 min, as a result, the tracker installation provided an increase in efficiency by 27% compared to the stationary system. However, the issue of automating the recording of experimental values of the photo panel remains unresolved in the work.

Study [9] focuses on the development of a two-axis tracking system that works on the basis of the photovoltaic method; it is shown that the studies were conducted for 5 days, with air temperature fluctuations from 9°C to 20°C. As a result, the two-axis tracker received 24.6% more energy than the panel installed stationary at an angle of 30°. The conclusions indicate that the system is less suitable for large photovoltaic plants, but for small and medium-sized arrays of panels it reduces the number of photovoltaic cells and investment costs. However, the issue of estimating the panel illumination values for building a model and conducting further predictions remains unresolved.

The use of four LDR sensors and a hardware base based on the Arduino UNO board for the development and testing of an active two-axis system is described in [10]. As noted, the proposed scheme demonstrated an increase in the energy efficiency of a small PV panel by 36.25% compared to a fixed panel, which can be used to power low-power devices. Experimental values show that the panel with Sun tracking generated a total of 314.27 W while the fixed panel generated 230.65 W in total. However, the problem of avoiding false tracker oscillations caused by a sharp change in illumination due to temporary cloud shading remains unresolved in the proposed prototype.

In [11], the implementation of a two-axis tracking system based on UV sensors is reported, which increase the accuracy of tracking the movement of the Sun and, accordingly, the amount of electricity generated. The implemented design showed the highest increase on sunny days, and under cloudy and low visibility conditions this increase decreased. The proposed installation receives information about the radiation intensity based on four UV sensors, the output data of which are compared with each other to ensure the movement of the pseudo-azimuthal structure and monitor the daily elevation angles. It is noted that this system increases energy generation by 19.97% compared to a fixed panel and by 11.00% compared to a tracker based on conventional LDR sensors. All this gives grounds to argue about the feasibility of using a tracker installation and the feasibility of considering replacing LDR sensors with more sensitive and fast-acting ones to increase tracking accuracy.

In study [12], a dual-axis solar tracker (DAST) was implemented based on the Arduino UNO microcontroller, servo motors for panel rotation, and light sensors – photoresistors. The installation controls the elevation angle in the vertical plane, and the azimuth angle in the horizontal plane, and an SD card is provided for recording the experimental results. The studies showed a power increase of 96% in the afternoon and 75% in the morning, with an average value of 33.16% relative to a fixed panel, increasing efficiency throughout the day. This gives grounds to argue that the tracking system is most effective in the afternoon, ensuring compliance with solar radiation when the static panel is turned to the side.

Paper [13] describes the development of a dual-axis solar tracking system using two sets of photoresistors, two DC motors, and a PIC16F877A microcontroller. One set of sensors provided tracking in the east-west direction according to the movement of the sun, the other in the north-south direction; the solar panel used for the study operated in the voltage range of 12–16.8 V. Hourly measurements, which were carried out on December 30, 2017 (8:00–19:00), showed that the two-axis tracking provides an increase of 31.4% more than the single-axis and 67.9% more compared to the fixed panel. However, the proposed approach has a low accuracy of the obtained results due to the high discreteness of the measurements. To solve this problem, it is advisable to optimize the process of recording experimental values, which would allow for a more accurate assessment.

Instead of photoresistors, which have a number of disadvantages and low speed with the need for external analog processing, integrated photoelectric sensors with on-chip signal processing or industrial photosensors with an I2C interface can also be used [14, 15].

Most studies focus on assessing the effectiveness of a specific design and algorithm of the tracker. The following typical gaps have been noted:

1. Insufficient attention to the automation of experimental data collection.
2. Limited assessment of the adaptability of algorithms to changes in illumination or local climatic conditions.
3. Use of sensors whose sensitivity and speed are not always sufficient for accurate tracking.

The task to ensure flexible replacement of tracking algorithms for studying their adaptability to changing illumination and climate conditions, automated collection and storage of experimental data, as well as the introduction of highly sensitive sensors with fast response to increase tracking accuracy, remains to be solved in full. This approach could eliminate those gaps and provide a qualitative assessment of the effectiveness of a two-axis tracker system.

3. The aim and objectives of the study

The aim of our work is to design a two-axis positioning system for photovoltaic converters, capable of automating the collection and storage of experimental data under online/offline mode, as well as to ensure the implementation and flexible change of tracking algorithms for conducting experimental studies. The results to be obtained would allow for a comparative assessment of the effectiveness of the tracking system under specific conditions of the installation area in accordance with the selected tracking algorithm.

To achieve the goal, the following tasks must be solved:

– to devise the concept and circuitry of a complex two-axis positioning system for photovoltaic converters for experimental studies and to assess the effectiveness of the tracking system under real climatic conditions;

– to conduct experimental studies and compare the effectiveness of different tracking algorithms; to evaluate the performance of the selected approach to tracking the Sun for a given area.

4. The study materials and methods

The object of our study is two-axis tracker systems for tracking the position of the Sun and monitoring the parameters of photovoltaic panels.

The following research hypotheses were adopted:

– in the case when photovoltaic cells are installed on a stationary (fixed) structure, in the morning and afternoon hours they significantly lose part of the insolation compared to mobile systems. In contrast, a two-axis tracker system that constantly adjusts the angles of inclination and azimuth in accordance with the selected algorithm enables optimal orientation of the panel to the Sun throughout the day, which should lead to a noticeable increase in electricity generation;

– the implemented system with the possibility of continuous data collection (online/offline) and flexible control over the choice of tracking algorithms makes it possible not only to compare the performance of different tracking methods in a specific climatic zone but also perform further economic calculations on the feasibility of implementing each algorithm in practice based on the resulting statistical data.

To objectively assess the efficiency gain, the designed biaxial system with constant online/offline monitoring was tested under actual conditions next to a static panel with the same parameters and load.

The parameters of the photovoltaic cells were recorded from sunrise to sunset on an SD card, and the illumination and air temperature were also recorded; the fixed panel was oriented at an angle of 45° to the south, which allowed us to assess the efficiency of the systems for the western region of Ukraine.

A two-axis solar tracker based on photoresistors uses four light-sensitive elements located around the perimeter of the panel – top, bottom, left, and right. These photoresistors continuously measure the level of illumination in their area. The ESP32 microcontroller reads these values and analyzes them to determine the direction of the greatest illumination. When the Sun changes its position, the illumination of the photoresistors becomes uneven. The microcontroller compares the values in two opposite pairs – top with bottom and left with right. If the difference exceeds a specified sensitivity threshold, the controller sends commands to the servo motors to correct the tilt of the panel. The cycle repeats until the illumination is leveled and the panel is directed exactly at the Sun.

Thus, the tracker constantly follows the sun, ensuring the most efficient capture of solar energy throughout the day.

For autonomous operation of the tracker installation, it is important to automate the process of determining sunrise and sunset and ensure the operation of the selected mode and these limits, to avoid additional settings and checks. It is advisable to use an algorithm that, based on geographical coordinates, would determine sunrise and sunset without the need for an Internet connection. The proposed installation uses the NOAA algorithm described in [16].

When calculating the hour angle, the value of the zenith angle is taken equal to 90.833°, which takes into account the correction for atmospheric refraction at sunrise and sunset. The value of the hour angle h_a is calculated according to the following formula (1)

$$ha = \pm \arccos\left\{\frac{\cos(90.833)}{\cos(\mathrm{lt})\cos(\delta)} - \tan(lt)\tan(\delta)\right\}, \quad (1)$$

where l_t is the latitude of the area; δ is the angle of declination.

To determine the value of the part of the year (in radians) φ, formula (2) is used

$$\varphi = \frac{2\pi}{365}\cdot\left(d - 1 + \frac{h-12}{24}\right), \quad (2)$$

where d is the day number in the year counted from January 1; h is the actual time in decimal format.

The time in minutes E_T and the declination angle δ of the Sun are determined from equations (3) and (4), respectively:

$$E_T = 229.18\cdot\begin{pmatrix} 0.000075 + 0.001868\cos(\gamma) - \\ -\ 0.032077\sin(\gamma) - \\ -\ 0.014615\cos(2\gamma) - \\ -\ 0.040849\sin(2\gamma) \end{pmatrix}, \quad (3)$$

$$\begin{aligned}\delta &= 0.006918 - 0.399912\cos(\gamma) + \\ &+ 0.070257\sin(\gamma) - 0.006758\cos(2\gamma) + \\ &+ 0.000907\sin(2\gamma) - 0.002697\cos(3\gamma) + \\ &+ 0.00148\sin(3\gamma).\end{aligned} \quad (4)$$

The time of sunrise S_R and sunset S_T of the sun is determined from equations (5), (6):

$$S_R = 720 - 4\cdot(l + ha) - ET, \quad (5)$$

$$S_T = 720 - 4\cdot(l - ha) - ET, \quad (6)$$

where l is the longitude of the area.

To ensure the correspondence of the inclination of the photo panel with respect to the solar radiation, it is necessary to determine the current position of the Sun in the sky at the appropriate time. For the correct operation of this algorithm, it is necessary to obtain data on the date, time, day number in the year, as well as the location of the tracking system. To achieve this goal, it is advisable to apply the calculation methodology described in [17]. The angles of inclination and azimuth obtained on the basis of the calculation allow for accurate positioning of the solar panel at a specific time.

For the operation of the algorithm, it is necessary to determine the solar declination δ for a specific day in the year according to formula (7)

$$\delta = -23.45°\cdot\cos\left[\frac{360}{365}(d + 10)\right], \quad (7)$$

where d is the ordinal number of the day in the year counted from January 1.

The local hour angle γ depends on the local solar time T, which is measured in hours, and the value 15° corresponds to the fraction of the Earth's rotation in one hour, and is determined from (8)

$$\gamma = 15^\circ \cdot (T - 12), \tag{8}$$

where T is the local solar time.

The values of the angles of declination α and azimuth β at a specific time are determined from equations (9) and (10):

$$\alpha = \sin^{-1} \cdot \left[\sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\gamma \right]; \tag{9}$$

$$\beta = \begin{cases} \cos^{-1}\left[\dfrac{\sin\delta \cos\varphi - \cos\delta \sin\varphi \cos\gamma}{\cos\alpha} \right], \gamma < 0^\circ \\ 360^\circ - \cos^{-1}\left[\dfrac{\sin\delta \cos\varphi - \cos\delta \sin\varphi \cos\gamma}{\cos a} \right], \gamma \geq 0^\circ \end{cases}, \tag{10}$$

where φ is the local latitude.

To compare the effectiveness of the tracker system, two installations were implemented, in particular a static one with the required orientation, and a two-axis tracker using both light sensors and planetary mechanics algorithms to determine the position of the sun.

5. Results of investigating the effectiveness of using a two-axis positioning system for photovoltaic converters

5. 1. Concept and circuit design of a complex two-axis positioning system for photovoltaic converters

Depending on the climatic conditions of the area, different types of tracking systems will have different efficiency and payback periods. The concept of the devised system is to provide the possibility of flexible change of tracking algorithms to study their efficiency, adaptability to changing lighting and climate conditions in combination with small dimensions and automation of experimental data collection. Also, to increase the accuracy of tracking, highly sensitive sensors with a fast response were used. This approach makes it possible to provide a qualitative assessment of the effectiveness of the two-axis tracker system under specific weather conditions of the geographical area.

For experimental research, a prototype of a complex two-axis positioning system for photovoltaic converters with the possibility of continuous online/offline monitoring was designed. The main component of the electronic circuit is the ESP32 microcontroller, which provides simultaneous operation of the positioning algorithm and the possibility of wireless connection to the network for monitoring and transmitting the necessary data. The proposed system, the structural diagram of which is shown in Fig. 1, allows synchronous switching between Offline (for field research) and Online (via local connection) modes without additional settings. To store experimental data, the circuit provides for the installation of an SD card, which is convenient and does not require connecting additional cloud services. Switching between Online/Offline modes, as well as control under Offline mode, is carried out using buttons with information displayed in the menu on the LCD display. Additionally, it is proposed to install a relay to control the heating element, which provides short-term heating of the lower frame of the photovoltaic cell when snow and ice freeze in winter. Sensors and transducers were used to monitor the parameters, in particular, the VELM7700 light sensor (Vishay Intertechnology, USA), the BME280 temperature and humidity sensor (Bosch Sensortec, Germany), the INA219 voltage and current sensor (Texas Instruments, USA), the DS3231 real-time clock chip (Maxim, USA), the HMC5883 three-axis magnetic sensor as a compass to determine the spatial orientation of the installation and the initial positioning of the HMC5883 photocell (Honeywell, USA). To obtain the illumination on the four sides of the photocell, GL5528 photoresistors were used. To ensure the necessary positioning along the azimuth and inclination axes, DS3218 servomotors were used.

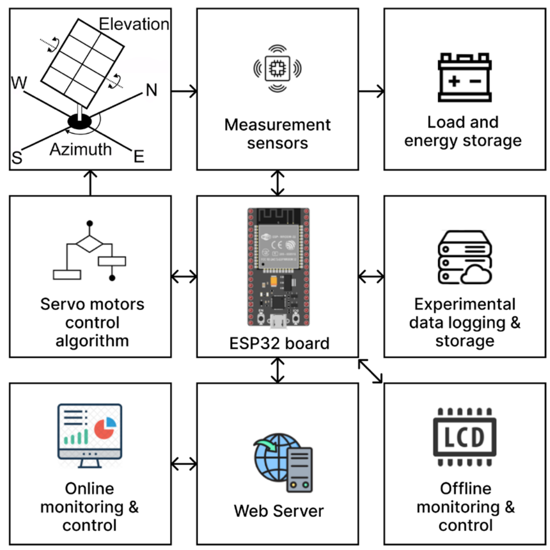


Fig. 1. Block diagram of the tracker installation

For online control, a web interface (Fig. 2) has been designed, which provides the user with access to all necessary information, enables dynamic switching of tracking algorithms and changes in the "recalculation" interval and updating of the current position, which is important for conducting experimental studies to assess the effectiveness of updating the inclination and azimuth angles over time.

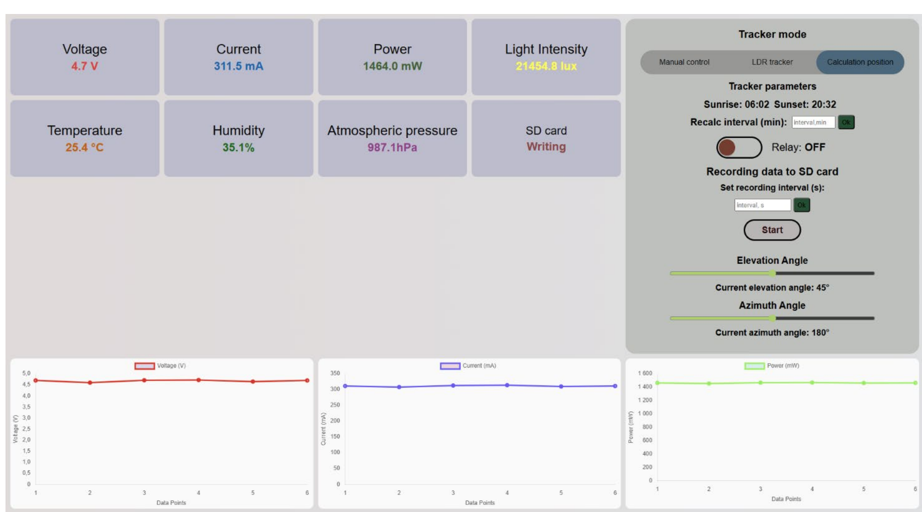


Fig. 2. Desktop version of the web interface for data management and display

The general view of the designed tracker system is shown in Fig. 3.

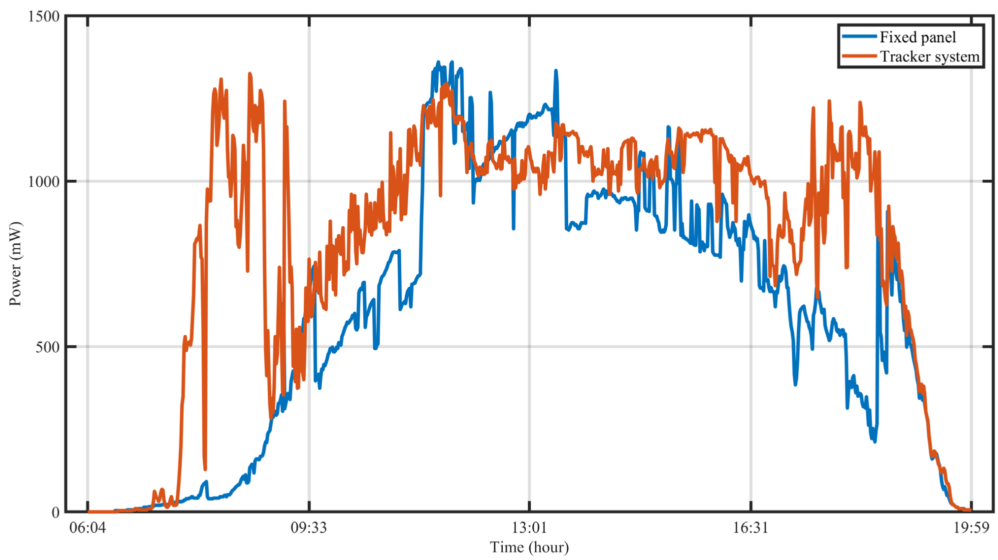
Fig. 3. Demonstration of the experimental setup

The system is designed in a compact housing with autonomous power supply and the ability to quickly replace the photo panel for conducting research on a specific type of photo panel in a specific area.

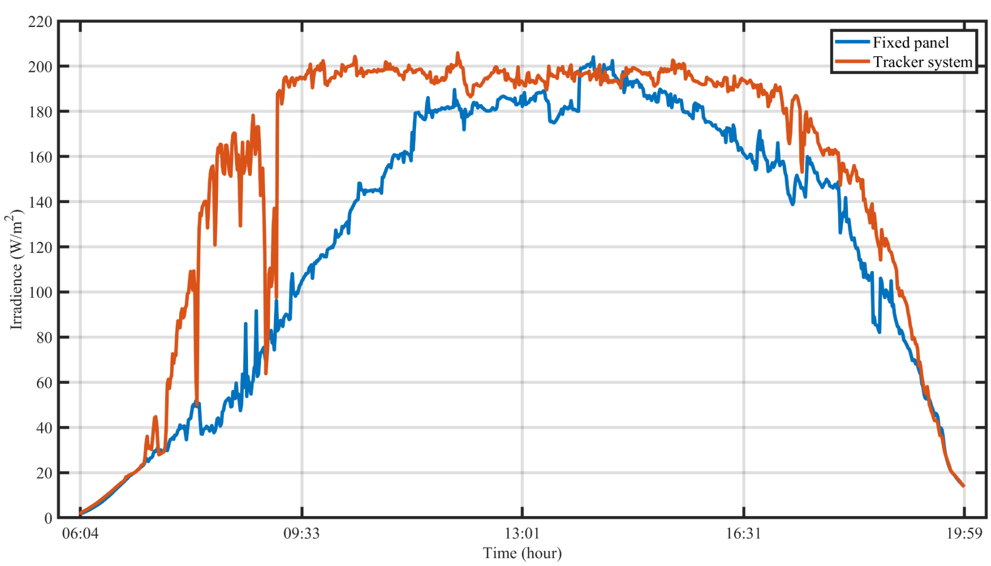
5. 2. Experimental results of the effectiveness of different tracking algorithms

Fig. 4, 5 show the experimental results of research on the effectiveness of two-axis training in comparison with a stationary photovoltaic panel. Measurements were carried out on a sunny spring day, sunrise time was 06:05 sunset time 20:00 (Fig. 4), and on a spring day with variable cloudiness, sunrise and sunset times were 06:02 and 20:04, respectively (Fig. 5).

The tracking system under the mode of the astronomical calculation algorithm provided the current angles of inclination and azimuth with updating of values every 10 minutes and recording of data with a discreteness of 1 minute. The panels were located in an area that was not shaded during the day.

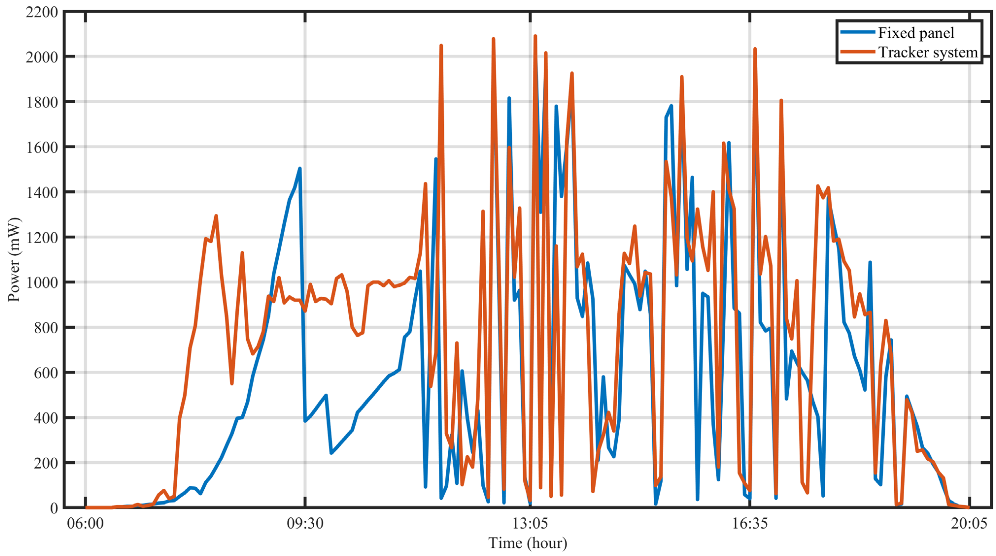


a

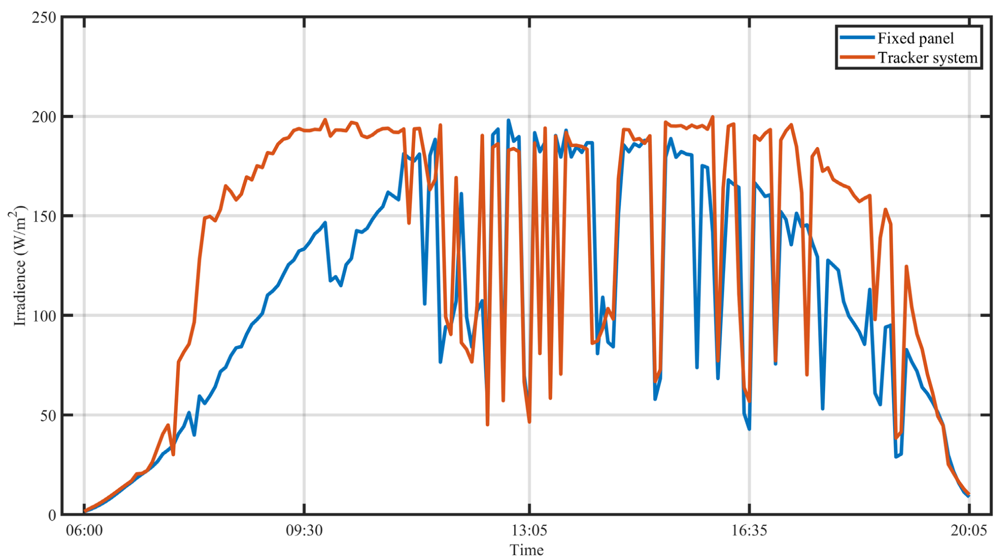


b

Fig. 4. Experimental curves on a sunny spring day for a static panel and a two-axis tracker installation: *a* – generated power; *b* – solar insolation



a



b

Fig. 5. Experimental curves on a spring day with variable cloudiness for a static panel and a two-axis tracker installation: *a* — generated power; *b* — solar insolation

Calculations of the increase in generated electricity were carried out according to formula (11), and illumination according to formula (12), respectively:

$$\Delta W = \frac{\sum W_{tracker} - \sum W_{fixed}}{\sum W_{fixed}} \cdot 100\%; \quad (11)$$

$$\Delta E = \frac{\sum E_{tracker} - \sum E_{fixed}}{\sum E_{fixed}} \cdot 100\%. \quad (12)$$

The high resolution of experimental data recording allows us to accurately calculate the increase in generated electricity and the increase in the level of illumination reaching the surface of the photovoltaic cell.

6. Discussion of results based on investigating the effectiveness of using a two-axis tracker system

The proposed approach to the flexible choice of tracking algorithms and the use of accurate sensors allows for an assessment of the effectiveness of the algorithms depending on variable climatic conditions. The designed system (Fig. 1), having a small size, makes it possible to conduct research on the effectiveness of various tracking algorithms and their adaptability to variable lighting and climate conditions, to conduct continuous monitoring of the parameters of photovoltaic converters, and to accumulate statistical data for a long period for a specific area.

According to our calculation results, according to equations (11), (12), on a sunny day it was possible to obtain 31% more electricity (Fig. 4, *a*) and 24.3% more illumination (Fig. 4, *b*). On a day with variable cloudiness, the increase in efficiency decreased and amounted to 24.1% of the generation capacity (Fig. 5, *a*) and 23.2% for illumination (Fig. 4, *b*). These results are well explained by the dependence of illumination and efficiency on the angle of incidence.

Special feature of our results is the simultaneous comparison of the illumination reaching the panel and its efficiency, which differs from existing research works [18, 19].

The obtained result is within the values reported by other researchers: compared to [8], +27%, and [9], +24.6%, the difference is small and is explained by the climatic features of the studied area.

The high efficiency of two-axis algorithms for accurate calculation of the Sun's position is shown by reducing unnecessary tracker movements, which in turn reduces their energy consumption and wear of moving parts.

In general, our experimental results showed a good match with those expected based on the analysis of literature sources.

Remote monitoring with a web interface and database made it possible to accumulate statistical data on the parameters of the photovoltaic converter over a long period of tracker operation.

Analysis of the obtained data allows for more accurate prediction of the payback of the tracker system.

In the practical application of the designed system, it is worth considering the dependence of efficiency of photovoltaic converters on the temperature of a photocell. Studies have shown that air temperature is not as informative an indicator as the temperature of the photocell.

The designed complex two-axis positioning system for photovoltaic converters with the possibility of continuous online/offline monitoring has significant potential for improvement.

In particular, it is planned to implement the possibility of monitoring the temperature of photovoltaic cells, which would make it possible to study the coefficients of reduction in the efficiency of solar energy conversion with increasing temperature and taking into account the corresponding reduction in economic calculations.

During the study, some limitations have been identified that cause a minor impact on the operation of the system; these include errors of measuring sensors due to temperature fluctuations, and minor deviations in determining the exact initial positioning of the panel, which are caused by surface irregularities and compass error when determining the exact orientation to the south.

Further development of our study involves accumulating statistical data over a long period of time and processing data by season, weather conditions, and terrain features.

7. Conclusions

1. The concept, circuitry, and control interface of a dual-axis positioning system for photovoltaic converters have been designed, which has enabled flexible changes in tracking algorithms to study their efficiency, adaptability to changing lighting conditions and climate in combination with automation of experimental data collection. The high efficiency of dual-axis algorithms for accurate calculation of the Sun's position has been shown by reducing unnecessary tracker movements, which in turn reduces their energy consumption and wear of moving parts.

2. Our experimental studies have shown that the dual-axis tracker system increases the efficiency of photovoltaic converters by 31% on a sunny spring day and provides approximately 24% increase on a day with variable cloudiness.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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