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A STUDY ABOUT A MICROCONTROLLER-BASED TRACKING SYSTEM FOR PHOTOVOLTAIC PANELS

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Abstract - ***A solution for the accomplishment of the tracking system for photovoltaic panels in order to increase the sun generated energy is presented in this work. The two axes of the tracking system are driven by two stepper motors in the suggested approach. The motors are supplied by L298N drivers and controlled by Arduino Mega board, based on the informations provided by light sensors. The sensors measure the intensity of the sunlight, these informations are processed by the ATMega microcontroller and function of these, in order to achieve the highest possible light intensity, the tracking system's axes will be rotated by the motors. The performances of the tracking system are monitored by Internet of Things concepts.***

Keywords**:** tracking system; photovoltaic panels; stepper motor; microcontroller.

1. INTRODUCTION

It is well known that in the recent years solar energy represents an increasingly used electric energy source, due to the fact that it is a clean, non-polluting and inexhaustible energy. The solar energy tends to replace to a large extent the electric energy obtained from other sources, such as fossil fuels, which produce a lot of pollution and the conventional resources used for energy production have decreased a lot.

The solar energy conversion systems aim to convert as much energy as possible from one form to another. There are multiple ways to accomplish this goal, including using high-performance photovoltaic panels, sophisticated algorithms for control, for the energy conversion and sunlight tracking devices to maximize solar energy collection. The well-known photovoltaic panels are used to convert the solar energy into electricity. These panels can be fixedly positioned, so the maximum amount of solar energy will not be utilized, or the panels can be attached to a mobile system with the help of which the position of the sun is tracked, in order to use its energy to the maximum.

The angle created by the direction of the sun's rays and the normal to the surface determines the consequences of exposing a surface to the sun. The function "cosinus" applied to this angle determines how much light reaches the corresponding surface. This explains the fact that the heating of the earth is different, at the poles being the lowest, because the surface in these areas is quite inclined to the sun's rays and at the equator the heating is the greatest.

The purpose of the sun tracking system is to give the solar panels two degrees of freedom to move in a way that keeps them always pointed directly at the sun and the sky. The solar ray tracking can be made in several ways. From the point of view of the principle of action, there are passive and active tracking systems. From the point of view of the materials used there are mono-crystalline or poly-crystalline solar panels, with thin film or amorphous silicon, biohybrid, cadmium telluride or concentrated solar cells [1]. From the point of view of the number of axes, there are tracking systems with one axis and with two axes. There are studies regarding the behaviour of the photovoltaic panels in different modes of operation, with the movement along a single axis [2,3] or along two axes. The tracking systems of the photovoltaic panels with movement along the horizontal axis are suitable for tropical areas, with the sun very high at noon and short days, while those with movement along the vertical axis are suitable for areas located at high latitudes, with long days in the summer.

The mobile system used for tracking the sun position is controlled by means of electric actuators, which, in turn, are controlled according to the signals received from the sensors that measure the intensity of sunlight. In theory, the photovoltaic panels' normal line moves in accordance to the sun's rays, with the panels' faces perpendicular to the rays' direction. This results in a (20-30)% increase in electricity production compared to a fixed system.

If a few years ago algorithms were starting to be developed to manage the operation of the maximum solar energy tracking system, nowadays these algorithms have become more and more intelligent. In [4], an algorithm is presented that uses the LabView program to improve the efficiency of photovoltaic panels. In [5], two control strategies are presented that keep the tracking errors lower than certain imposed values, respectively the average annual cosine losses are below a certain imposed value. Most tracking systems use light sensors to detect the quantity of solar energy each moment. According to [6] the yield of systems with photovoltaic panels is calculating by dividing the produced electrical energy to the absorbed solar energy on the photovoltaic systems, taking into account the atmospheric conditions and the angle of incidence of the solar radiation on the panels.

Many researchers use microcontrollers to manage the motors' motion which drive the tracking system, as in [7-12]. The used motors are usually DC motors and the tracking systems are guided by the sun's coordinates in height and by the motion of the sun from east to west.

There are open-loop and closed-loop systems. The open-loop systems use mathematical algorithms to determine the movement of the tracking system. Closed-loop systems with feedback track the sun using mathematical models. The microcontroller uses exact azimuth and elevation coordinates to identify the sun's location and then instructs the motors to move the solar panels in the sun's direction at predefined time intervals.

There are situations when the photovoltaic panels must be mounted on floating platforms or other aquatic constructions and in these cases the variants used for tracking systems use the gyroscope to follow the angular motion of the sun, engine movements and angular displacements, including PID control [13].

Some researches present monitoring systems of photovoltaic panels, with the recording of output data and their maintenance when needed. The performance of photovoltaic panel systems can often be affected. There are researches for the realization of real-time monitoring systems through IoT, of photovoltaic panels, using a network with wireless sensors and microcontrollers that check the temperature and radiation at their level, the data being stored in the Cloud. By determining the sun's location according to the solar time, which depends on the angular movement of the sun, the geometry of the system can be obtained [14-18]. The movement of the photovoltaic panel is usually based on an algorithm that compares the values measured by the opposite sensors (East-West, North-South), the error is calculated and this will be the input value for the microcontroller.

In [19] an analog solution with 4 light sensors, 2 for each rotation axis of the photovoltaic panels, 2 stepper motors and a digital solution using a microcontroller and 3 sensors is presented by comparison. There are sun tracking systems that are based on the acquisition of panoramic images with the help of a fisheye camera [20]. The azimuth and elevation coordinates of the sun are estimated via digital processing of these photos, provided to a microcontroller that will command a gyroscope.

Since it was found that electromechanical tracking systems consume quite a lot of energy, solutions were sought that use controllers with programmable technology Photovoltaic panels can be electronically modeled either by one diode or by two diodes. In an effort to lower energy usage, the microcontroller that commands the electrical drives of the tracking system, during the pause intervals, enters a working mode with reduced energy consumption [21].

The solar energy tracking systems made for photovoltaic panels must be made in such a way that they work correctly in any area of the globe, with the optimization of energy consumption. The systems that use light sensors are sensible to the dust, humidity and other severe weather conditions, the best solution would be the mathematical calculations for the sun position and then the corrections will be done for the position of the photovoltaic panels. When designing the mechanical part of the tracking system also must be taken into account the wind force that could afect the panels [22].

A modern technique uses special controllers to obtain the maximum amount of energy, along with fuzzy logic or AI and machine learning [23]. In the near future, predictive algorithms will be increasingly used together with real-time data, to anticipate weather conditions, to improve the operation and efficiency of photovoltaic panels, to identify potential problems that may arise during the operation of photovoltaic panels [24].

The structure of the paper is as follows. First, an introduction was made and a short presentation of other researches about the mobile photovoltaic systems. In the second chapter, "Mathematical description of the sun's position relative to the photovoltaic panels", the main quantities (angles) and the mathematical relations that describe the sun's location with respect to the earth are presented. The following chapter, "Implementation of the sun tracking system's hardware and software" contains informations about the different components of the mobile photovoltaic system, as well as the algorithm by which the system works. Next, in the "Experiments and results" chapter some measurements and charts, made in Oradea, are presented. The last chapter "Conclusions" presents the main achievements of the work, as well as new research directions in this field.

2. MATHEMATICAL DESCRIPTION OF THE SUN'S POSITION RELATIVE TO THE PHOTOVOLTAIC PANELS

In the recent years, more and more photovoltaic panels have been installed all over the globe, including on the territory of Romania. The evolution of installed power in the period 2022-2024, in Romania, can be seen in the graph in Figure 1.

The electrical energy produced by photovoltaic panels can be successfully used to power both domestic and public consumers, such as traffic lights, lighting fixtures on the street or in parks, various indicators, fans or other devices at home or in industry, etc. The ubiquitous and continuous internet connectivity offers the possibility of using remote monitoring and control devices, in real time, of many things, including photovoltaic panels, through the Internet of Things.

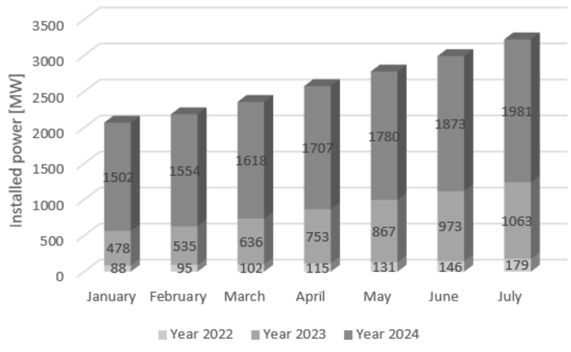

Figure 1. The evolution of the power installed by the prosumers connected to the distribution networks

Sensors are used for measuring the intensity of sunlight, humidity and temperature sensors, sensors for measuring energy, power, current and voltage, LCD display, etc.

Some notions are necessary to understand the operation of photovoltaic panels: *the latitude* - indicates a point's angular location on the surface of the earth, either north or south of the Equator and has values between 0° (at the Equator) and 90° (at the poles), *lat*, expressed in degrees and minutes; *the incidence angle* - the angle formed by the sun's incident ray and the normal to the incident surface; *the declination angle* - the angle formed by the projection of the imaginary line connecting the earth's center and the sun's center on the earth's equatorial plane (*decl*); *the elevation angle* (altitude) - the angle made by the sun with the earth's horizon line (*el*); *the zenith angle* $zen = 90° - el$ - the angle formed by the vertical axis and the line connecting the earth's and the sun's centers; *the inclination angle* represents the angle formed by the solar panel and the horizontal axis, being a type of incidence angle; *the azimuth angle* - is measured in a spherical coordinate system and represents the angle formed by the line between the earth's center and the sun's center projected on the horizontal plane and the north direction (varies between 0 and 90 degrees), measured from the east (*az*). Some of these quantities result from Figure 2.

The relation (1) is frequently used to determine the sun's position based on its altitude [8]:

$$\mathrm{el} = \sin^{-1}[\cos(\mathrm{lat}) \cdot \cos(\mathrm{decl}) \cdot \cos(\omega) + \sin(\mathrm{lat}) \cdot \sin(\mathrm{decl})] \quad (1)$$

The azimuth angle, *az*, is calculated using the relation [3]:

$$\mathrm{az} = \cos^{-1}[\sin(\mathrm{el}) \cdot \sin(\mathrm{lat}) - \sin(\mathrm{decl})]/[\cos(\mathrm{el}) \cdot \cos(\mathrm{lat})] \quad (2)$$

The zenith angle, *zen*, is calculated as follows in relation (3):

$$\mathrm{zen} = 90° - \mathrm{el} \quad (3)$$

The solar hour angle, *ω*, has the following expression:

$$\omega = (T_s - 12) \cdot 15 \quad (4)$$

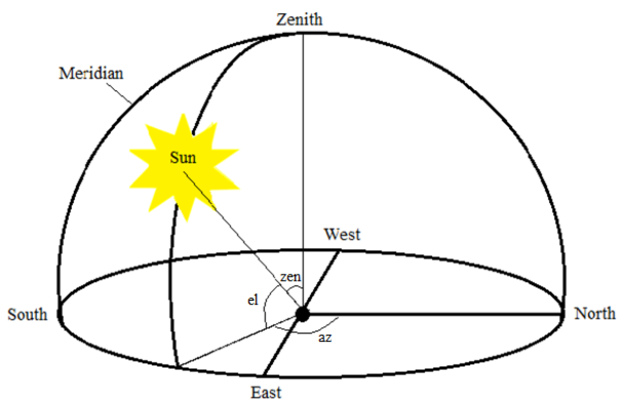

Figure 2. The angles of the sun to the earth

where T_s is the local solar time and 15 is the amount of degrees the earth spins in an hour (360°/24 hours = 15°). The declination angle, *decl*, can be calculated with the following relation [22]:

$$\mathrm{decl} = 23.45 \cdot \sin\left[\frac{360°}{365} \cdot (284 + \mathrm{D})\right] \quad (5)$$

where D is the current day from the calendar.

For the construction of the control algorithm of the sun position monitoring systems, the previously provided angles - which were computed with the aid of relations (1) through (5) - are crucial. The rays of the sun must always be at right angles to the photovoltaic panels' surface in order to produce the most electricity. In Figure 3 is presented the orientation of the photovoltaic panels in different moments of the day.

Observing the sun's line starting from east till west, respectively from south to north, the photovoltaic panels must have 2 axes of rotation, one horizontal and one vertical, as it can be seen in Figure 4.

The photovoltaic panels produce direct voltage and therefore an inverter is needed to transform direct voltage into alternative voltage. In general, photovoltaic panels produce more energy than is consumed, therefore it is necessary to store it in batteries or inject it into the national electricity network.

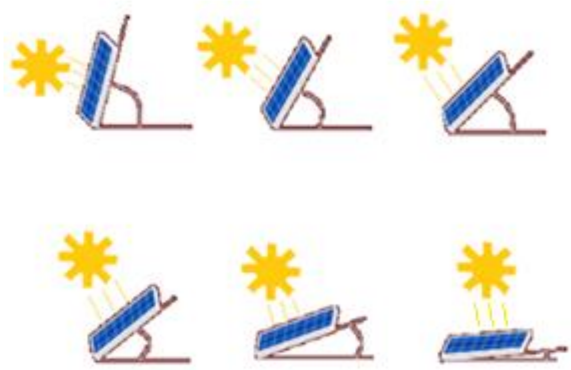

Figure 3. The orientation of the photovoltaic panels

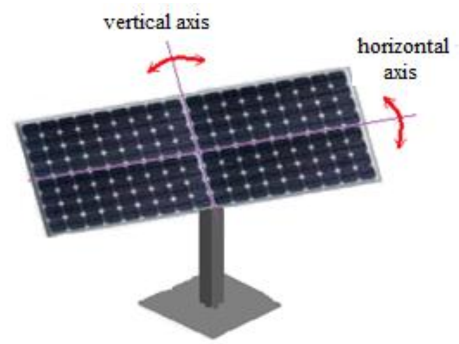

Figure 4. The axes of the photovoltaic panels

The energy stored in the batteries can be used in cases of emergency, at night or on cloudy days.

For the most precise positioning of the photovoltaic panels, it is considered that the angles for their orientation to the sun and to the horizontal plane, in a system with two axes, are calculated as follows [3]:

$$\beta_1 = az \quad (6)$$

$$\beta_2 = \frac{\pi}{2} - el \quad (7)$$

and the displacement of the panels is obtained with the relation:

$$d = c \cdot \cos\left(\frac{\cos\beta_2}{\cos(lat)}\right) \quad (8)$$

where: $c = 0.409 - 0.5016 \cdot \sin(\omega_s + 1.047)$ (9)

ω_s being the hour angle at sunrise.

3. IMPLEMENTATION OF THE SUN TRACKING SYSTEM'S HARDWARE AND SOFTWARE

The proposed solution for the system that will follow the sun is a dual-axes system, each axis being driven by a stepper motor, for a very precise positioning, SMH - the stepper motor for the horizontal axis and SMV - the stepper motor for the vertical axis. Each motor is connected to the Arduino board through the L298N driver. Four light sensors are utilized to measure the amount of light coming from sun. Actually the sensors are resistors those resistance depends on the light intensity and they are fixed on the photovoltaic panel, LU - up sensor, LD - down sensor, LL - left sensor, LR - right sensor. Each sensor will be oriented towards one of the cardinal points: east, west, south and north.

The use of these sensors is very effective on days with a lot of sun, with clear skies, but it is ineffective on days with clouds and unstable weather. That's why, apart from the sensors, it is useful to use an algorithm that is programmed in the microcontroller to know at every moment where the sun is and which will determine the positioning of the photovoltaic panel accordingly. This algorithm is based on the relations (1) - (9). In Figure 5 a block-diagram of the system is presented.

The system that tracks the sun's position is connected to the internet, using a Wi-fi Arduino compatible shield ESP 8266. The data acquisition system provides the values from the sensors, as well as the tilting situation of the panel, the calculated azymuth and the elevation of the sun, the temperature of the panel and of the environment, the amount of absorbed solar energy and its output data being included in an internet SQL database. To measure the solar irradiance on the photovoltaic panel, a device called pyranometer is used. All these devices connected through the internet network are part of Internet of Things concept, that allows the automatic data transfer and a complete automatic control of the tracking system of the photovoltaic system.

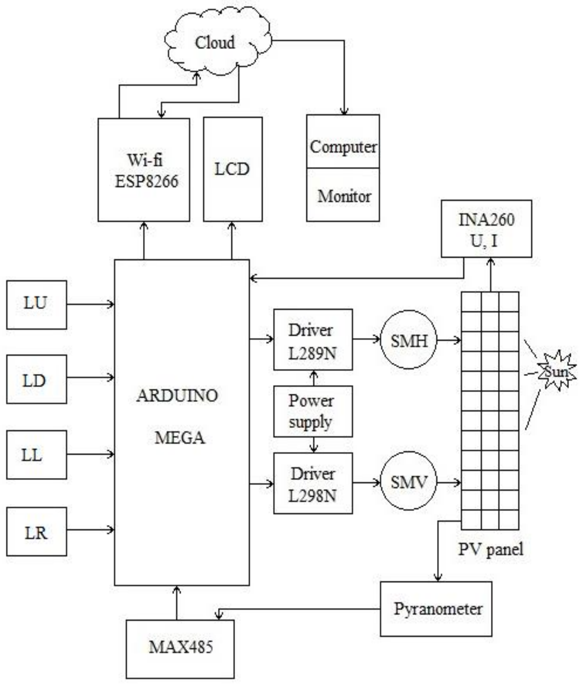

Figure 5. The connection diagram of the system components

The platform hosting the project is Amazon Web Services (AWS). It offers many services, including Cloud provider, infrastructure provider for calculations, storage, databases, as well as a number of contemporary technologies including artificial intelligence, machine learning, analyse of data and the Internet of Things. All this gives ease, speed, hosting of applications in real time with remote monitoring, with very good performances.

The algorithm based on the light sensors followed by the mobile system is presented in Figure 6. First, the values of the light sensors are read and the motors are initialized.

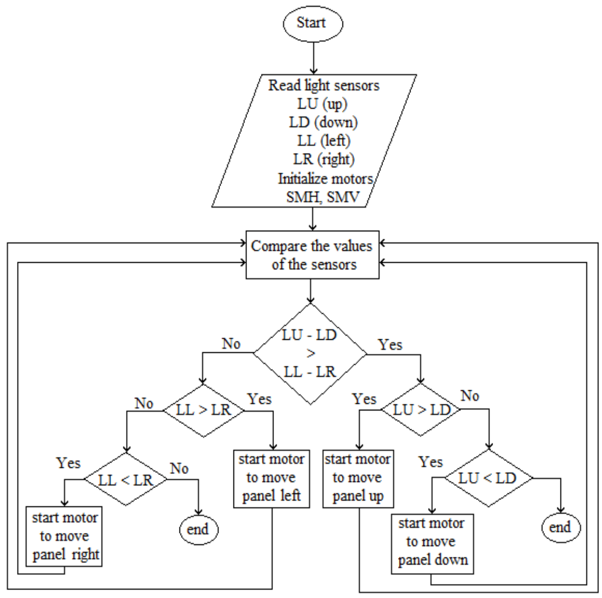

Figure 6. The representation of the light sensor algorithm

Then the differences between the values of the opposite sensors are compared (up-down, respectively left-right) and depending on the result of this comparison, the values of the opposite sensors will be compared to give the command to the motors to rotate the photovoltaic panel straight to the sun, by moving up-down, respectively left-right.

The mechanism for tracking the sun’s position is sofisticated and the microcontroller will always operate in a way that uses few energy, the environmental conditions being analyzed, also. The movement of the panel will be done only if the solar radiation increases and exceeds a certain threshold. Also, the operation of the tracking system when performing each step will be limited by the program to 500 ms. All this is imposed to minimize the energy consumption of the tracking system.

4. EXPERIMENTS AND RESULTS

The features of the photovoltaic panel utilized in the experiments are listed in Table 1.

Table 1.The features of the photovoltaic panel

Module type	Polycristalline
Rated power (max)	260 W
Voltage in open-circuit	37.8 V
Current at short-circuit	9.01 A
Voltage at maximum power	30.7 V
Current at maximum power	8.5 A

The stepper motors that operate the panels in both vertical and horizontal directions are powered by 12 V and have a step angle of 1,8°.
The experiments were done for two photovoltaic systems, a fixed one and a dual-axis the other one, in a sunny day of 6^{th} of July, 2024, in Oradea, the temperature outside being about 34 degrees. Each of them has 6 photovoltaic panels as type of that from Table 1. The generated voltage, current and power of the photovoltaic panels were measured, the obtained values being structured in Table 2. It is evident that the voltage and output power reach their greatest values between 12 pm and 6 pm, with the values sharply declining before 12 pm and after 6pm. Also, the values measured with the fixed system are with (20-30)% lower than those measured with the tracking system, which certifies the advantages of the panels with dual-axis tracking system.

Table 2. The measured values for the fixed and tracked panels

Time	Voltage_ fixed [V]	Voltage_ tracked [V]	Current_ fixed [A]	Current_ tracked [A]	Power_ fixed [W]	Power_ tracked [W]
9 am	83.12	130.52	6.85	7.27	569.372	948.8804
11 am	135.32	161.64	7.33	7.69	991.8956	1243.0116
1 pm	145.66	168.06	7.35	7.78	1070.601	1307.5068
3 pm	152.31	169.64	6.99	7.21	1064.6469	1223.1044
5 pm	144.76	164.81	6.53	6.81	945.2828	1122.3561
7 pm	86.22	113.53	6.25	6.55	538.875	743.6215

An increase in the power of tracking systems compared to fixed systems was calculated, on average by approximately 30%, which is a great advantage. Comparisons of the voltages, currents and powers achieved in two scenarios - for stationary panels and mobile panels - are shown in Figures 7, 8 and 9 and Figure 10 shows the global average irradiation per month.

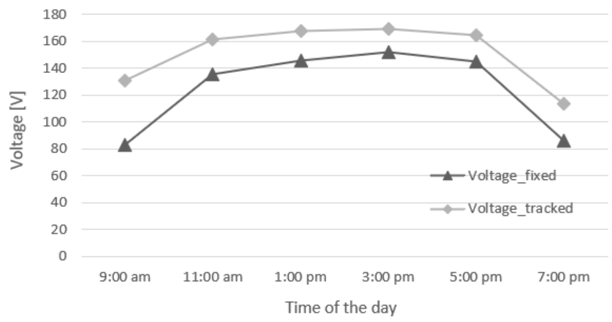

Figure 7. The measured voltage in the two cases

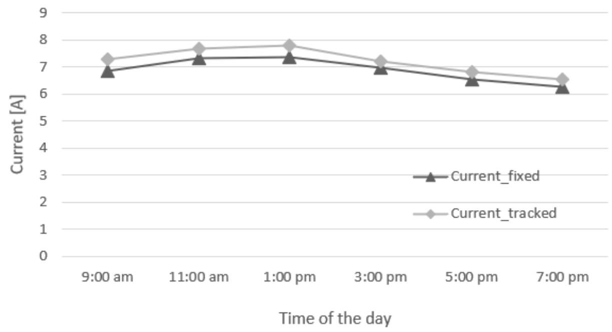

Figure 8. The measured current in the two cases

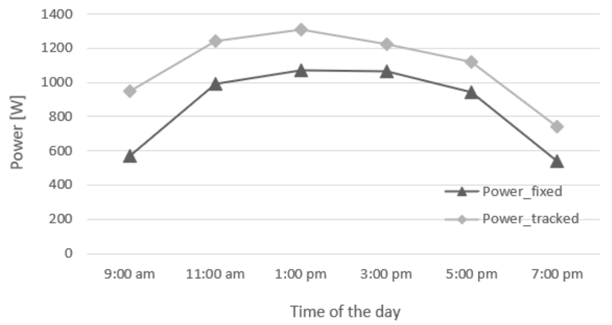

Figure 9. The measured power in the two cases

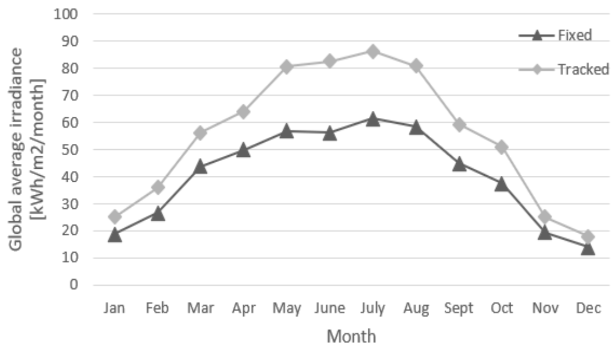

Figure 10. The global average irradiance over the year

5. CONCLUSIONS

The objectives of this paper were the following: highlighting the necessity of switching from traditional electrical energy sources to renewable ones, especially the sun's energy; understanding that by moving the photovoltaic panels so that they follow the sunlight, maximum energy is obtained; the movement of the panels along the horizontal and vertical axis can be done through a hybrid algorithm based on light sensors and on the calculation of the sun's position, based on the date and the panels' location; the control of the drive motors of the panel axes is done from the microcontroller and the data is monitored through the Internet of Things.

In the future work, depending on the weather conditions, the panels' condition (dust, moisture) and the amount of solar radiation, machine learning and artificial intelligence algorithms will be employed to maximize the performance of the photovoltaic panels' tracking system.

Conflict of Interest

The author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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