



PLC Controlled Dual-Axis Solar Tracking System Using Astronomical Equations

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Accepted 28 November 2022

Abstract

In recent years, climate change and the global energy crisis have increased the interest in renewable energy. Solar, wind and hydraulic energy, which are among the renewable energy sources, are the areas where the most investments are made. Of these three renewable energy sources, solar energy has the highest growth rate. In order to increase the electrical energy obtained from the sun, more efficient panels are being produced. Also, one of the good ways to increase the amount of energy produced by solar panels is to expose the solar panel to more solar radiation. This is possible if the angle between the panel and the sun is always perpendicular. Therefore, the panel should focus on the sun and receive the highest solar radiation according to the sun's daily and seasonal movements. In this study, firstly, the classification of solar tracking systems used for solar panels to follow the sun is explained. Then, the method of calculating azimuth and elevation angles using astronomical equations is given. Finally, the hardware and software details of the control of the solar tracking system with PLC using astronomical equations are presented.

Key words: Solar tracking system, sun tracker, dual-axis, PLC, astronomical equations.

1. Introduction

Energy is important for the social and economic development of people. Energy plays a critical role in both the production and consumption of goods and services. Therefore, the energy needs of countries are increasing day by day [1]. As energy production dependent to fossil fuels, it brings fundamental problems such as climate change and environmental pollution. The increase in the need for energy production from environmentally friendly, clean, cheap and sustainable sources has increased the interest in renewable energy sources. Photovoltaic systems are seen as one of the important resources in meeting all these needs [2]. The sun emits energy at the level of 3.8×10^{23} kW per second. Approximately 1.08×10^{14} kW of this energy reaches the earth's surface, which is approximately 150 million km away from the sun. The rest is reflected back into space and absorbed by the atmosphere. The total annual solar radiation arriving on the earth is more than 7500 times the world's total annual primary energy consumption of 450 EJ (1 EJ = Exa Joule = 10^{18} J) [3,4]. The energy potential of the sun is so great that it holds great promise to meet the world's ever-increasing energy demand. In recent years, new technologies have been developed to generate energy from solar energy using both direct

and indirect techniques [5]. In general, active solar technology can be divided into two categories: (i) photovoltaic technology and (ii) solar technology. In recent years, photovoltaic panels containing semiconductors have been used to convert sunlight directly into electrical energy. The efficiency of these panels has increased up to approximately 46% and has become an important option to be preferred [6,7]. In addition, solar energy will be one of the options to meet the future energy demand, as it is superior to other renewable energy sources in terms of modularity, usability, accessibility, capacity, efficiency and cost effectiveness [8].

The main factors affecting the output power of photovoltaic (PV) panel cells are the panel direction, the angle of incidence of the photons, the material of the solar cells and environmental effects. Solar tracking systems are used to increase the amount of radiation received by PV panels from the sun. This allows the solar panel to track the sun in the most suitable position to produce the highest power output. Interest in solar tracking systems is increasing as it makes it possible to obtain the optimum amount of solar energy [9]. This interest is evidenced by the rapid increase in studies on solar tracking systems in recent years. As can be seen in

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Figure 1, there has been a significant increase in the last six years. Figure 2 shows the number of studies

conducted in various countries on solar tracking systems [7,10].

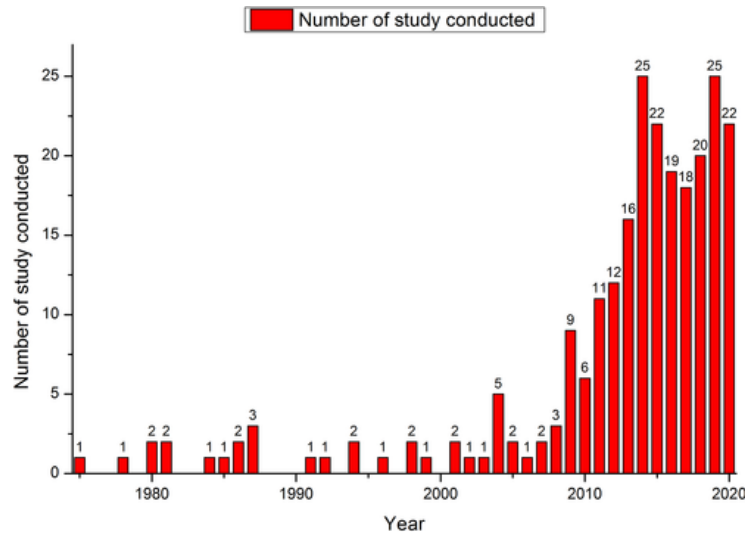


Figure 1. Solar tracking system studies by years [7].

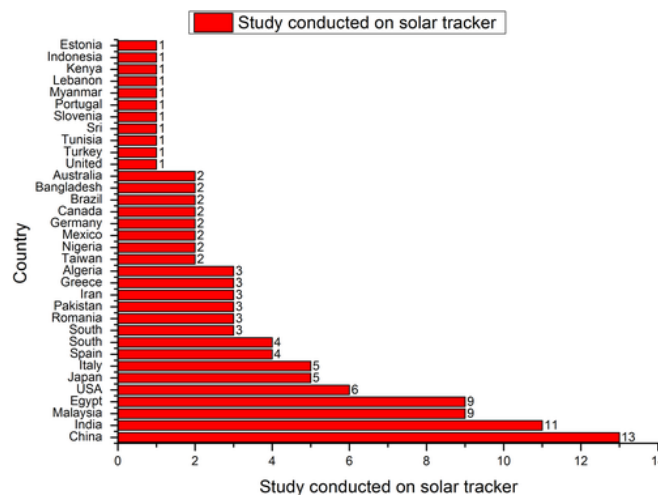


Figure 2. Number of studies conducted in various countries on solar tracking systems [7].

2. Classification of Solar Tracking Systems

Solar tracking systems can be generally classified based on driver type, control type, tracking strategy and degree of freedom in four categories. Figure 3 shows a general diagram of the classification of solar tracking systems.

2.1. Solar Tracking Systems by Driver Type

Solar tracking systems can be classified as active, passive and chronological solar trackers according to driver type. (i) Active trackers use sensors, actuators and electric motors to continuously track the sun. The information received from the sensors is processed in the processors, driving the motion system and helping to align the panels perpendicular to the solar radiation. (ii) Passive trackers are

designed for the panel to track the sun without any mechanical drive. Passive tracking systems consist of thermo-hydraulic actuator, bimetallic-thermal actuator and shape memory alloy thermal actuators. The thermo-hydraulic actuator relies on low boiling compressed gas which turns into liquid from solar heat. This fluid causes the structure of the tracker to move towards an imbalance. This is called a thermo-hydraulic actuator mechanism. The bimetallic-thermal actuator mechanism works with a system based on the thermal expansion of bimetallic strips. The metals that make up the bimetal consisting of aluminum and steel have different expansion coefficients with temperature. That's why aluminum bends more than steel, and this bending creates a movement. It is classified as a shape memory alloy

thermal actuator mechanism. Shape memory alloy (SMA) is a type of smart material. It is deformed by temperature change and regains its former shape with the effect of shape memory. This material, which creates movement with a force to regain its former shape, shows a thermo-mechanical feature [11-13].
(iii) Chronological trackers follow the sun using the

earth's rotation direction and rotation speed. That is, a chronological solar tracking system is a time-based tracking system in which the panel moves at a constant speed and a fixed angle throughout the day and for different months. The motor or actuator is controlled to rotate at low speed (about 15° per hour) [9, 10].

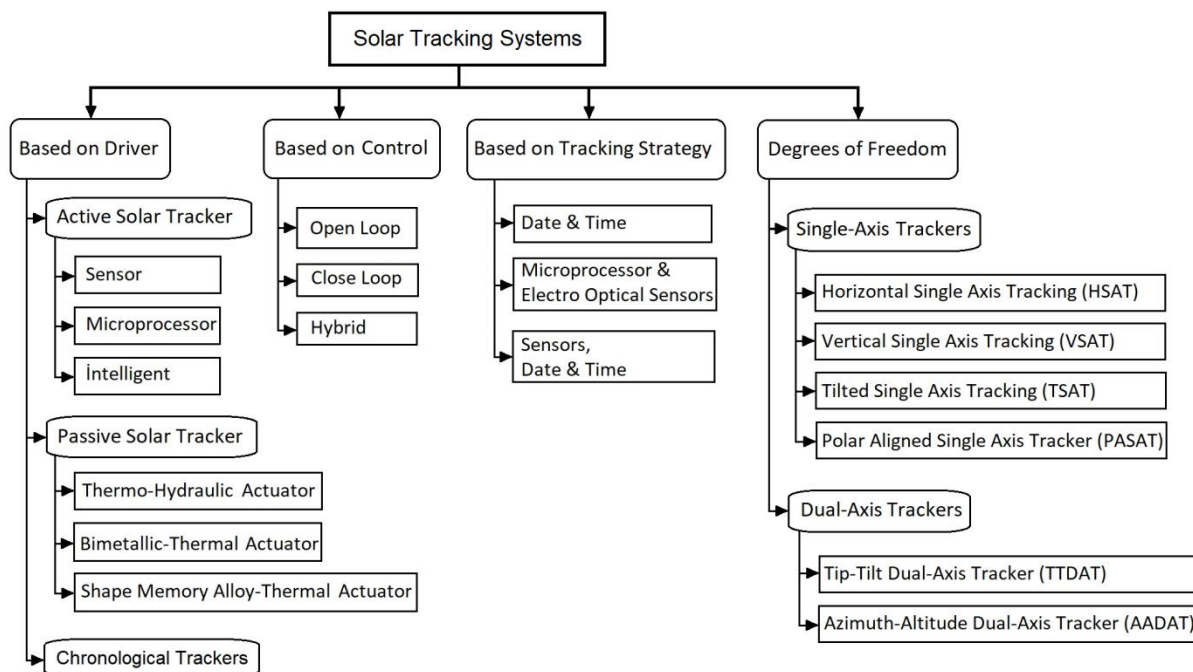


Figure 3. Classification of solar tracking systems

2.2. Solar tracking systems by the type of control

According to their control types, Active solar trackers can be classified as open loop, closed loop and hybrid controlled solar trackers. (i) Open loop controlled solar tracking systems are based on a control algorithm that only depends on the date, time and geographic location information of the solar panel. The solar tracking system with an open-loop control system has the ability to track the sun regardless of weather conditions. However, it requires an accurate time source and accurate geolocation information. It also requires proper initialization and system setup. (ii) Closed-loop controlled solar tracking systems have dynamic tracking control algorithms. It uses a feedback signal from a sensor to determine the sun position. The closed-loop control system used in solar tracking systems may be simpler in practice than an open-loop one. However, due to its reliability, requirement for sensor cleaning and bad weather conditions, it may track the sun incorrectly. (iii) Hybrid controlled solar tracking systems use open-loop and closed-loop solar tracking strategies together. A typical hybrid sun

tracking strategy alternates between open and closed loop algorithms [14].

2.3. Solar tracking systems by the tracking strategies

Active solar tracking systems are divided into three category according to the tracking strategy: -using date and time, -using microprocessor and electro-optical sensor, and -using sensor, time and date. (i) Trackers using the date and time determine the position of the sun thanks to algorithms that use this information as input data. The microprocessor uses the angle information obtained with the help of the algorithm that uses geographical location, time and date to control the actuators and motors. (ii) Trackers using microprocessor and electro-optical sensors have an interface that presents data from electro-optical sensors to the microprocessor as input data. The sensors are used to measure the sunlight intensity and transmit it to the microprocessor. Then control signals are generated by the microprocessor to control the motors. (iii) Trackers using sensors, date and time use a combination of the three

elements mentioned. They contain a hybrid monitoring system controlled by a microprocessor. These systems consist of sensors and inputs such as data/time to analyze the performance of the tracker [5, 11].

2.4. Solar tracking systems by degree of freedom

Solar trackers can be classified according to their degrees of freedom as single-axis and dual-axis solar trackers. (i) Single-axis trackers are trackers that have one axis of rotation and come in four variants. These are the horizontal single axis trackers (HSAT), vertical single axis trackers (VSAT), inclined single axis tracker (TSAT) and polar aligned single axis trackers (PASAT). The HSAT tracks the daily north-south movement of the sun along its horizontal axis of rotation to the ground. VSAT tracks the daily east-west movement of the sun along its rotation axis perpendicular to the ground. TSAT sets the axes of rotation between the horizontal and vertical axes.

Thus, the daily east-west movement of the sun is tracked by adjusting the axis of rotation to be parallel to the axis of rotation of the earth. PASAT is aligned to the pole star. Thanks to this, the angle of inclination becomes equal to the latitude of the installation, allowing it to be aligned with the earth's axis. (ii) Dual-axis trackers have a technology that has two axes of rotation and can be divided into tip-tilt biaxial trackers (TTDAT) and azimuth-altitude biaxial trackers (AADAT). Generally, TTDAT monitors the sun's daily east-west movement and the sun's north-south movement by rotating the PV panel fixed to the top of the pole. AADAT can track the sun's daily east-west movement and the sun's daily north-south movement using a large floor-mounted ring. In Figure 4, single- and dual-axis solar tracking system types are shown [15].

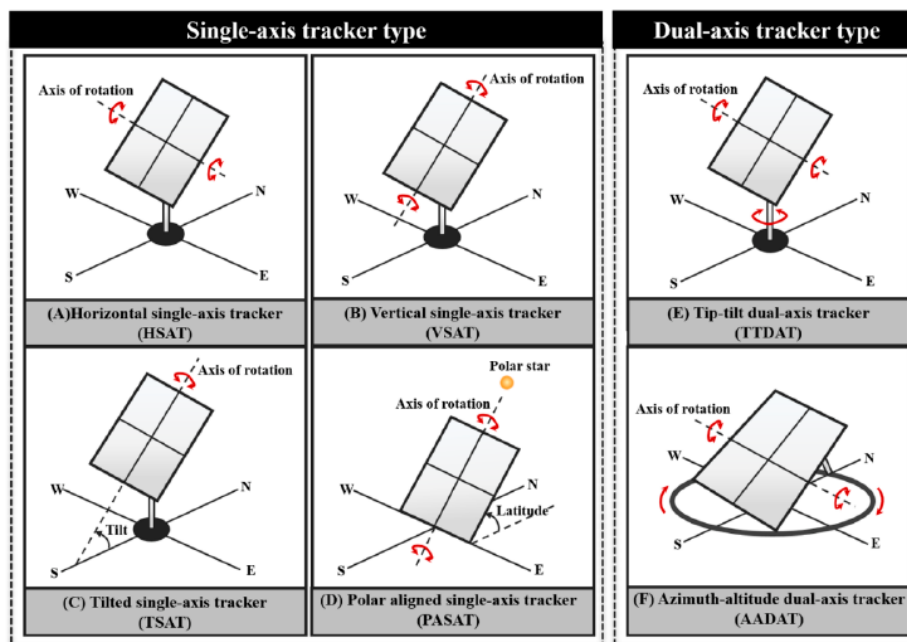


Figure 4. Single-axis and dual-axis tracker types.

3. Calculation of Azimuth and Elevation angles using Astronomical Equations

The input variables of the method given here are the latitude (Lat), longitude (Lon), altitude (Alt) of the location whose Azimuth and Elevation angles will be calculated, and the time as the year (Y), month (M), day (D), hour (H), minute (Min), and second (Sec) at the same location.

The steps of the method are as follows [16]:

1. First, the Julian day number (JD) of the time when the sun angles is calculated:

$$JD = \left\lfloor 365.25(Y + 4716) \right\rfloor + \left\lfloor 30.6001(M + 1) \right\rfloor + 2 + \left\lfloor \frac{Y}{100} \right\rfloor + \left\lfloor \frac{Y}{4} \right\rfloor - \left\lfloor \frac{Y}{100} \right\rfloor + D - 1524.5 + \left(\frac{H + \frac{Min}{60} + \frac{Sec}{3600}}{24} \right) \quad (1)$$

in this equation, $\lfloor \cdot \rfloor$ is the integer value function.

2. In the next step, the day number (*Day*) is calculated with the following equation:

$$Day = JD - 2451543.5 \quad (2)$$

3. The orbital angles of the sun relative to the earth are then calculated:

$$w = 282.9404 + 4.70935 \cdot 10^{-5} \cdot Day \quad (3)$$

$$e = 0.016709 + 1.151 \cdot 10^{-9} \cdot Day \quad (4)$$

$$M = Mod(356.0470 + 0.9856002585 \cdot Day, 360) \quad (5)$$

The variables *w*, *e* and *M* in these equations are defined as Perihelion longitude [deg], eccentricity angle [deg] and average anomaly [deg] respectively.

4. The mean longitude angle of the sun (*L* [deg]) and the elliptical tilt of the sun (*oblecl* [rad]) is calculated with the following equations.

$$L = w + M \quad (6)$$

$$oblecl = 23.4393 - 3.563 \cdot 10^{-7} \cdot Day \quad (7)$$

5. An auxiliary angle (*E* [deg]) for the eccentricity of the solar orbit is found with the help of the following equation.

$$E = M + \frac{180}{\pi} \cdot e \cdot \sin(M) \cdot (1 + e \cdot \cos(M)) \quad (8)$$

6. The perpendicular coordinates in the elliptical plane are calculated:

$$x = \cos(E) - e \quad (9)$$

$$y = \sin(E) \cdot \sqrt{1 - e^2} \quad (10)$$

7. These coordinate values are converted to distance (*r*) and true anomaly (*v*):

$$r = \sqrt{x^2 + y^2} \quad (11)$$

$$v = a \tan 2(y, x) \quad (12)$$

Function *a tan 2()* in the last equation is a four-quarter inverse tangent function.

8. The longitude (*lon*) of the sun is calculated:

$$lon = v + w \quad (13)$$

9. The elliptical orthogonal coordinates of the sun is calculated:

$$xeclip = r \cdot \cos(lon) \quad (14)$$

$$yeclip = r \cdot \sin(lon) \quad (15)$$

$$zeclip = 0 \quad (16)$$

10. Elliptical orthogonal coordinates are converted to equatorial coordinates:

$$xequat = xeclip \quad (17)$$

$$yequat = yeclip \cdot \cos(oblecl) + zeclip \cdot \sin(oblecl) \quad (18)$$

$$zequat = yeclip \cdot \sin(0.409115648642983) + zeclip \cdot \cos(oblecl) \quad (19)$$

11. The conversion from equatorial coordinates to spherical equatorial coordinates is done with the following equations:

$$r = \sqrt{xequat^2 + yequat^2 + zequat^2} - \frac{Alt}{149598000} \quad (20)$$

$$RA = a \tan 2(yequat, xequat) \quad (21)$$

$$delta = a \sin(zequat / r) \quad (22)$$

12. The local star time is calculated:

$$UTH = H + \frac{Min}{60} + \frac{Sec}{3600} \quad (23)$$

$$GMTS0 = \frac{Mod(L+180,360)}{15} \quad (24)$$

$$SIDTIME = GMTS0 + UTH + \frac{Lon}{15} \quad (25)$$

13. The value RA is replaced by the hour angle value HA [deg]:

$$HA = SIDTIME \cdot 15 - RA \quad (26)$$

14. Conversion to the orthogonal coordinate system is done:

$$x = \cos\left(HA \cdot \frac{\pi}{180}\right) \cdot \cos\left(delta \cdot \frac{\pi}{180}\right) \quad (27)$$

$$y = \sin\left(HA \cdot \frac{\pi}{180}\right) \cdot \cos\left(delta \cdot \frac{\pi}{180}\right) \quad (28)$$

$$z = \sin\left(delta \cdot \frac{\pi}{180}\right) \quad (29)$$

15. Conversion to a horizontal axis in the east-west direction is made:

$$xhor = x \cdot \cos\left((90 - Lat) \cdot \frac{\pi}{180}\right) - z \cdot \sin\left((90 - Lat) \cdot \frac{\pi}{180}\right) \quad (30)$$

$$zhor = y \quad (31)$$

$$zhor = x \cdot \sin\left((90 - Lat) \cdot \frac{\pi}{180}\right) + z \cdot \cos\left((90 - Lat) \cdot \frac{\pi}{180}\right) \quad (32)$$

16. Finally, the azimuth and elevation angles are calculated:

$$Az = a \tan 2(yhor, xhor) \cdot \frac{180}{\pi} + 180 \quad (33)$$

$$El = a \sin(zhor) \cdot \frac{180}{\pi} \quad (34)$$

4. Hardware structure and software of PLC controlled solar tracking system

The dual-axis solar tracking system shown in Figure 5 uses astronomical time equations to allow the PV panel to follow the sun at the desired location of the world. By increasing the nominal power of the driver circuit and the motor of the system, larger PV systems can also be provided to follow the sun. The solar tracking system consists of the equipment shown in Figure 6. These equipment are respectively an operator panel HMI (Human Machine Interface), a PLC (Programmable Logic Controller), two stepper motor drivers and motors. Also a power supply with 24V DC 3A outputs used for power supply of the system. In addition, the skeleton of the system was built using sigma aluminum profiles.



Figure 5. General view of the implemented solar tracking system.

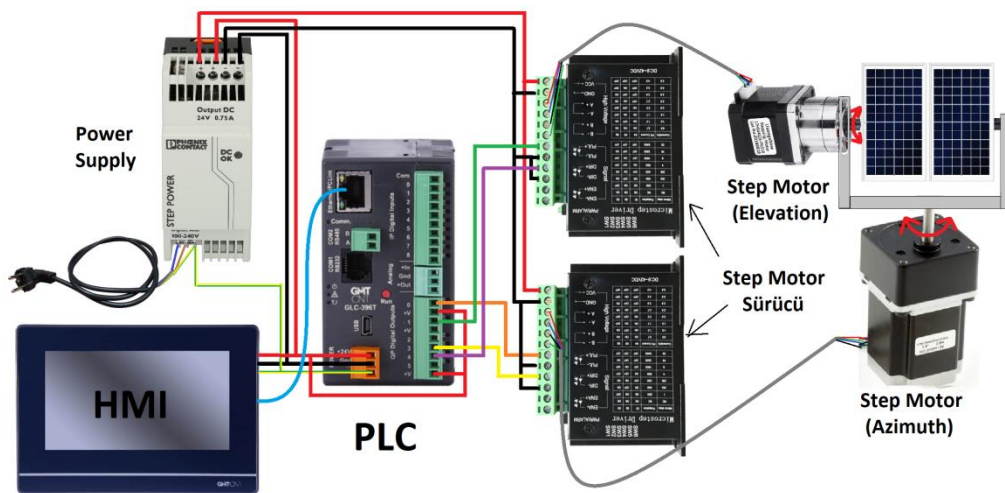


Figure 6. The equipment that makes up the solar tracking system

During the commissioning of the solar tracking system, the necessary steps must be completed on the operator panel, respectively. At the end of each process step, the next step is passed with the forward button on the operator panel. In the first step, latitude, longitude and altitude information that gives the position of the PV panel on the world is entered on the operator panel. In the second step, the real time clock and date information is entered. In the third step, the reference starting position of the PV panel is created. For this, by using the east-west and north-south keys, the position of the PV panel is adjusted so that it is exactly north and full horizon, and its angles are reset and assigned as the starting position. In the fourth step, it is selected according to which degree of freedom the solar tracking system will follow the sun. In this step, four different selections can be made on the screen: fixed, azimuth tracking, elevation tracking and dual axis tracking. When fixed is selected, the panel switches to the orientation page for the desired azimuth and elevation angle. By entering the azimuth and elevation angles on the screen, the panel can be positioned at the desired angles with the direction key. When it is requested to follow in the direction of the azimuth angle, the orientation page is switched to enter the fixed elevation angle. By entering the elevation angle on the screen, the panel is positioned to the desired elevation angle with the direction key. Thus, the elevation angle does not change when tracking is initiated. When it is requested to follow in the direction of the elevation angle, the orientation page is switched to enter the fixed azimuth angle. By entering the azimuth angle on the screen, the panel is

positioned to the desired azimuth angle with the direction key. Thus, the azimuth angle does not change when tracking is started. When double axis tracking is selected, the system proceeds to the next step without any action. In the fifth step, the first option "Start Tracking" and the second option "Show Tracking Activity" can be selected. The first choice is that the system starts tracking by going to the required angles according to the current real time clock. The second selection allows the system to accelerate the tracking movement of the panel in the entered simulation time (minutes) for the time between the start and end times of a desired date. For this, after the start and end times are entered, positioning is done with the "Go to Start Position" button so that the panel returns to the position at the start time. Then, the movements of the panel are started by pressing the "Show Tracking Movement" button.

4. Conclusion

Solar tracking systems increase power output by allowing PV panels to receive more solar radiation. The power outputs of PV panels obtained with single and dual axis solar tracking systems are different. The effect of single or dual axes moving according to the position of the PV panels on the power output differs. This indicates that single or dual axis solar tracking systems should be evaluated in terms of power output and installation costs. In this respect, the selection of the most suitable solar tracking system is important. In this study, hardware and software information of a PLC controlled solar tracking system is given by using astronomical time

equations. A simple commissioning can be performed with an operator panel in the system. The system can operate in any desired location in the world. Without changing the operator panel and PLC in the system, the power of the stepper motors and drivers can be updated so that the panels with the

desired dimensions can follow the sun. The system can be operated in different tracking modes (fixed, single axis and double axis). With the feature of displaying the tracking movements of the system, the user can test and monitor the panel movements.

Acknowledgments

This study was supported by the project numbered PYO.MUH.1908.22.029 within the scope of

Ondokuz Mayıs University Scientific Research Projects (BAP).

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