Journal of Power Technologies 100 (1) (2020) 32–42

Design and Implementation of Control Algorithms for Single-Axis Sun Tracking Systems

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Abstract

Solar energy is the most widespread renewable energy source due to the modular structures of PV modules and low maintenance requirement. In this study, a sun tracking system is proposed with a view to achieving a generated energy output than with a fixed PV system. There are two different control structures and algorithms are proposed to control the sun tracking system to increase efficiency. The tracking system uses algorithms to determine the exact position of the sun at any time during the day and to turn the PV modules to a position perpendicular to the sun. In the first control circuit, the position of the sun is precisely found with two identical LDRs and an angle sensor. In the second control circuit, the position of the sun is tracked by using a real time clock and an angle sensor to limit the platform. Greater energy generation is achieved by turning existing solar panels to face the sun. Furthermore, a data acquisition device stores and monitors daily irradiation data on a computer and the data entered in the database are used to produce graphic interfaces.

Keywords: Solar tracking, maximum power point tracking (MPPT), solar power plant, photovoltaics, renewable energy sources.

1 Introduction

Climate concerns and the cost of fossil fuel-based energy generation have driven research and investment in renewable energy sources (RESs). Solar and wind energy are outstanding RESs due to their wide potential all over the world. Solar energy is a reliable and safe energy source due to it being pollution free and having long lifetime and low maintenance costs. The overall power efficiency of any photovoltaic (PV) system is limited by the PV module efficiency, which is around 14 .. 17% for polycrystalline and 17 .. 22% for mono-crystalline modules. On the other hand, the system losses of power converters and cables in a PV system may be up to 25%. Hence, several novel research campaigns have sought to increase the efficiency of the PV power conversion system. One prominent method to enhance overall efficiency is maximum power point tracking (MPPT) which plays a vital role in increasing PV system efficiency [1]; [2]. Solar irradiation reaches the Earth in (i) direct beam carrying about 90% of the solar energy, and (ii) diffuse sunlight. Since the majority of the energy is in the direct beam, turning the PV module to track the sun at a perpendicular angle for as long as possible increases the converted energy level [3]; [4]. Therefore, installing PV systems in the right place is of great importance in terms of energy efficiency. Several studies have been performed to improve the tracking efficiency of PV modules. In a study carried out in Singapore, three different tracking methods were applied. Sensors placed at various angles and directions were used to detect the exact irradiation data for three years, which was made subject to analysis. The angle and direction data obtained from sensors located at different positions of PV systems and from equatorial countries were analyzed to acquire data to increase the energy output of PV plants [5].

Several studies surveying and focusing on sun tracking systems can be found in the available literature. A portable sun tracking system following the sun on a single axis was compared with the fixed solar panel having the same characteristics in one study and the sun tracking system produced more energy and had more heat on it [6]. In another study, it was observed that the sun tracking system works more efficiently than the fixed system, although the sun tracking system itself consumes energy [7]. Mechanical and electrical designs can be improved for tracking the sun. The position of the sun can be detected by light dependent resistors (LDRs) located on the system, where control of the sun tracking system is performed by a fuzzy logic algorithm. A comparison between one tracking system and a fixed PV system having the same features revealed that the sun tracking system provides an efficiency increment of approximately 47% [8]. Single axis solar trackers include horizontal single axis trackers, vertical single axis trackers, tilted single axis trackers and polar aligned single axis trackers. Single axis trackers are essential to increasing daily energy output, since they operate in the east-

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west direction. However, the solar axis shifts around 46 degrees in the north-south direction owing to the equatorial shift of the Earth and sun through the year. Therefore, the seasonal direct beam angles reaching a PV plant differ.

Dual axis trackers provide freedom of rotation with the additional N-S axis, which is lacking in the single axis tracking system. Dual axis trackers are classified by the orientation of their primary axis with respect to the ground. The two most widely known types of implementation are tip-tilt dual axis trackers and azimuth-altitude dual axis trackers [9]. The horizontal and vertical tracking ability of the dual axis trackers allow for optimum solar energy levels. One actuator moves the rack in the north-south direction while anther one moves it in the east-west direction. Thus, the primary actuator shifts the plant to the most accurate alignment against seasonal progression while the second actuator increases the daily generation potential [9]; [10].

It is calculated that a dual-axis sun tracking system generates between 17% and 25% more energy than a fixed system in sunny weather and around 8% and 11% in cloudy weather [11]. Dual-axis portable sun tracking systems have been produced using LDR sensors and two servomotors, as presented in references where sun tracking systems improve efficiency in output voltage and output power [11]. In another study, a portable sun-tracking system operating on the double axis is designed using five LDRs located at different nodes. The operation of the system was tested by creating a control algorithm for the sun tracking circuit installed and the error rate of the system was calculated as being 5 degrees [4]. Li et al. proposed a system with an irradiation detector that is designed to measure the shadow on four LDRs on a dual axis sun tracking application. A new algorithm proposed for use in the control circuit provides control for the system [12]; [13].

Novel systems and algorithms are being developed to increase the efficiency of PV systems. In the study given in [14], a prediction algorithm for solar angles was developed using the second derivative of energy for PV systems. The algorithm developed wascom pared with previous fixed and sun tracking systems. It was observed that this tracking system operates more efficiently than other systems on an annual basis. In addition to sun tracking systems supported by various sensors, sensorless sun tracking systems are subject to research. Experimental studies have shown that there is an increment of 28.8%-43.6% in the sun tracking system depending on the season [15].

In the proposed infrastructure, the MPPT controller was implemented with a sensorless sun tracking system. While the proposed system has the advantages of previous PV systems installed with or without sensors, it has eliminated disadvantages of these systems. In the study, the PV system is used itself as a sensor. According to the values obtained from the PV system, the position of the sun is determined and the platform where the PV modules are mounted tracks the sun. The sun tracking system shown in Fig. 1 is designed to increase the generated energy in existing PV systems. The sun is tracked in the east-west direction as a single axis with the PV system placed on one pillar for easier movement. A platform is manufactured to mount the panels and the pillar, and later the platform is mounted on the pillar. After the design and implementation of the mechanical base is completed, the electrical design is performed. A control circuit, LDR, DC motor drive circuit, angle sensor, real time clock and linear actuator are used in the electrical design of the system. Two different control circuits were developed to control the sun tracking system. In the first control circuit, the actual position of the sun is detected with two LDRs located in the east and west directions. Once the sun's position is determined, the control circuit activates the linear motor to rotate the PV system to the required position. Thus it ensures that the PV systems are perpendicular to the sun during the day.

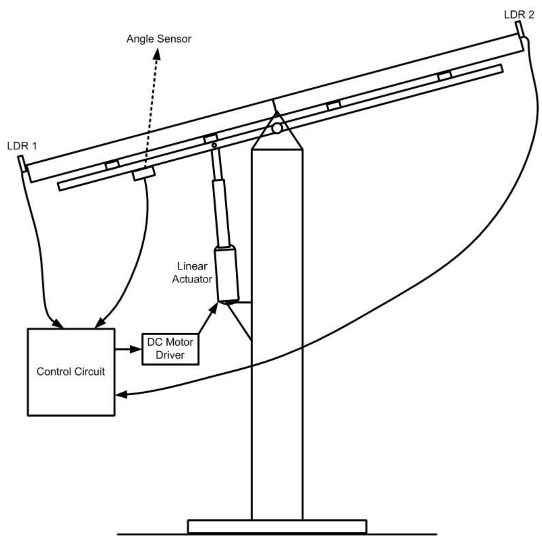

Figure 1: Sun tracking system

The position of the PV system is controlled by the angle sensor used in the system and excessive PV system rotation is prevented. In the second control circuit, the angle sensor and the real time clock are used to track sun. The sun tracking system is turned relative to the specified position regarding time. A control algorithm was developed to track the sun successfully and to provide maximum energy generation.

The studies conducted in the literature generally focus on portable sun tracking systems [4,6-13]. The limited number and smaller sizes of PV module used in such systems use smaller motor drives and motors in sun tracking systems. Therefore, it is not clear how successful the proposed portable systems will be in actual sun tracking applications.

In the proposed study, the implemented tracking system is applied in a realistic PV plant, which can be extended to similar modules to increase the yielded energy level. The controller is designed and improved in single axis tracking to limit the power consumption of the tracker system and increase efficiency. The tilt axis is calculated to reflect the geographical and irradiation data of the site. The solar plant consists of six 200W PV modules generating 1200Wp output power. The platform where the PV modules are fixed is designed according to a micro plant model that can be increased to construct PV module strings. The implemented sun tracking system can be controlled by either sensored infrastructure or a real time clock-based controller. Moreover, another control algorithm was developed to run both control structures together.

The second section presents the feasibility and analyses studies of the proposed sun tracking system, while mechanical design and implementation studies are given in the 3rd section. The electrical design, control systems and algorithms and remote monitoring software are presented in sections 4, 5, and 6th sections respectively

2 Sun Tracking System Proposed

The generated energy of a PV system depends on the irradiation and inclination angles, where the fixed systems require neat calculations to detect the exact angle. The elliptical shape and tilt angle of the Earth causes varying levels of irradiation depending on the location. Furthermore, the seasonal movement of the Earth changes the irradiation angle of the sun at any exact place in the different seasons. Therefore, the energy efficiency of PV systems depends on the azimuth and tilt angles [5].

Conventional fixed PV installations are made in light of seasonal irradiation angles and sunny day potential. Alternative installations to increase the irradiation angles in daily and seasonal periods are implemented in single-axis and dual-axis structures [14]. Single-axis systems increase the daily energy output since they move in the east-west direction while dual-axis trackers have an additional north-south tracker that adjusts the tilt angle [16]. The annual azimuth and tilt angles of the site where the PV plant installed are shown in Fig. 2 for spring, summer, fall and winter respectively.

The proposed sun tracking system is installed in Nevsehir, Turkey at 38.676N, 34.746E as indicated in Fig. 2 . The geometrical position of the Earth relative to the sun is calculated for the selected installation site as shown in Fig. 3. The key geometrical angles to define the current position are latitude angle (ϕ), longitude angle (l), declination angle (δ) and hour angle (ω). The related angles such as zenith angle (z), altitude angl (α_s) and azimuth angle (γ_s) are obtained by using the geometric angles. The precise calculation of the incident solar radiation is obtained by three additional variables: surface tilt angle (β), wall-azimuth angle (γ) and incidence angle (i).

The declination angle (δ) of the sun to the equatorial plane varies according to seasonal changes. The angle δ at 12 noon can be calculated as seen in Eq. 1 and Eq. 2 [14]; [17]

$$\begin{aligned}\delta = (0.006918 - 0.399912\cos B\\ +0.070257\sin B - 0.006758\cos 2B\\ +0.000907\sin 2B - 0.002697\cos 3B\\ +0.00148\sin 3B)\left(\frac{180}{pi}\right)\end{aligned} \quad (1)$$

$$\delta = 23.45\sin\left(\frac{360\,(n+284)}{365}\right) \quad (2)$$

where B is given in Eq. 3 depending the day number (n) counted from January

$$B = 360\,\frac{(n-1)}{365} \quad (3)$$

The solar hour angle (ω) is the movement of the local meridian caused by solar displacement in the east-west direction; it is negative in the morning and positive in the afternoon, as depicted in Eq. 4 [14]; [18] where t_s is solar time:

$$\omega = (ts - 12)\,15^\circ \quad (4)$$

The altitude angle α_s that is the angle between the sunbeam of direct solar radiation and the horizontal line of the sun is calculated by where δ is declination angle, ϕ is latitude angle, and ω is solar hour angle as seen in Eq. 5:

$$\alpha_s = \sin^{-1}\left[\cos\omega\cos\delta\cos\phi + \sin\delta\sin\phi\right] \quad (5)$$

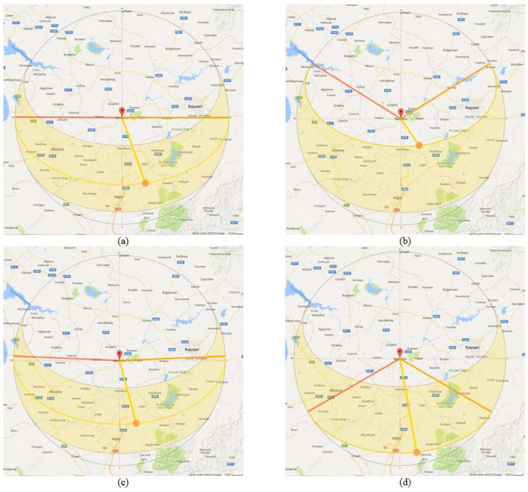

Figure 2: Seasonal azimuth and tilt angles of the site (a) spring (b) summer (c) fall (d) winter.

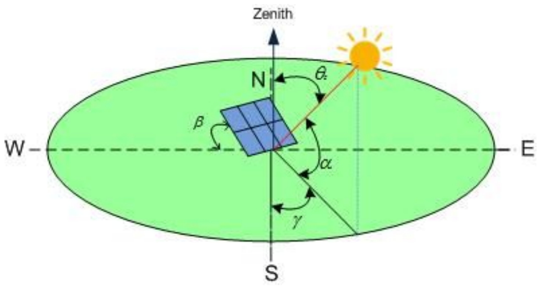

Figure 3: Solar irradiation angles

The azimuth angle γ_s, zenith angle $\varsigma o \sigma \theta_z$, and inclination angle $\varsigma o \sigma \theta_z$ are calculated as follows [14]; [17]; [18]; [19]; [3]:

$$\gamma_s = \cos^{-1} \frac{[\sin\alpha \sin\phi] - \sin\delta}{\cos\alpha \cos\phi}$$

$$\cos\theta_z = \cos\omega \cos\delta \cos\phi + \sin\delta \sin\phi$$

where the azimuth angle γ_s yields the tilt angle of PV modules as $\theta_z = \beta$:

$$\begin{aligned} \cos\theta = {} & \sin\phi \sin\delta \cos\beta \\ & - \cos\phi \sin\delta \sin\beta \cos\gamma \\ & + \cos\phi \cos\delta \cos\beta \cos\omega \\ & + \sin\phi \cos\delta \sin\beta \cos\gamma \cos\omega \\ & + \cos\delta \sin\beta \sin\gamma \sin\omega \end{aligned} \quad (6)$$

The PV modules are mounted on the installation at the tilt angle β that is calculated as seen in Fig. 4.

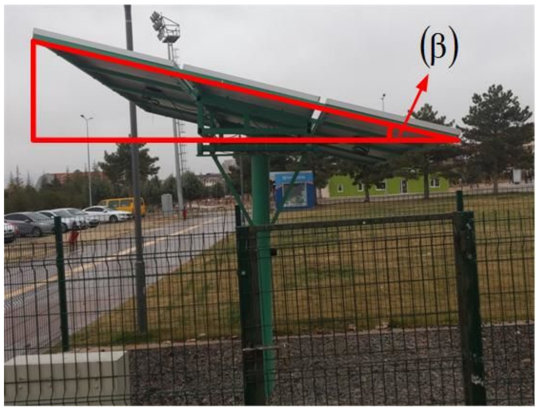

Figure 4: PV modules mounted at calculated tilt angle β

3 Mechanical Design of Tracking System

It is important to design a mechanical design that is useful, robust and easy to maintain in sun tracking systems. Therefore, the available literature on design of sun tracking systems was examined before designing the mechanical system [10]; [13]; [20]; [21]; [22]; [23]. It has been observed that sun tracking systems are placed on a platform that is carried by a base on the centre of gravity (CG). The base placed on the CG facilitates the movement of the tracking system. In addition, the required moment of inertia when moving the system is less than similar alternatives [8]. Therefore, it is decided that the sun tracking system should be installed on one base pillar in this study.

The mechanical design is planned considering the PV modules to be installed in the sun tracking plant. The plant is configured to supply 1200Wp power generated by six PV modules where each has 200Wp output power. The dimensions of the panels, 1580mm*810mm*35mm, are taken into account for the mechanical and static design of the carrier platform and the base. Although there are several mounting selections available as related in the literature, the platform is planned to be carried by the base on a single pillar connected to the CG point, and the platform shape is modelled to be in a square shape. The overall dimensions of the mechanical system is calculated considering the total area and tracking angles, which are limited to exact values to handle the inertia of the platform by the actuator. The base height and di-

Table 1: Components and weights

Component	Number	Weight (kg)	Total Weight (kg)
PV Module	6	15-May	93
Platform and racks	1	120	120
Total			213

ameter are also calculated considering the weight and inertia of the mounting platform with PV modules. The total weight of the system is measured at around 213kg as listed in Table 1.

The dimensions, mounting holes, and modelled platform drawings are seen in Fig. 5. The rear side of the platform and the mounting racks modelled are illustrated in Fig. 5 .c where the PV modules are mounted on the platform by eight screws, to improve mechanical durability. The calculations and mechanical modelling studies were tested and implemented using AutoCAD mechanical design software. The mechanical design of the sun tracker analyzed is shown in Fig. 5 .d with the linear actuator to perform the movement.

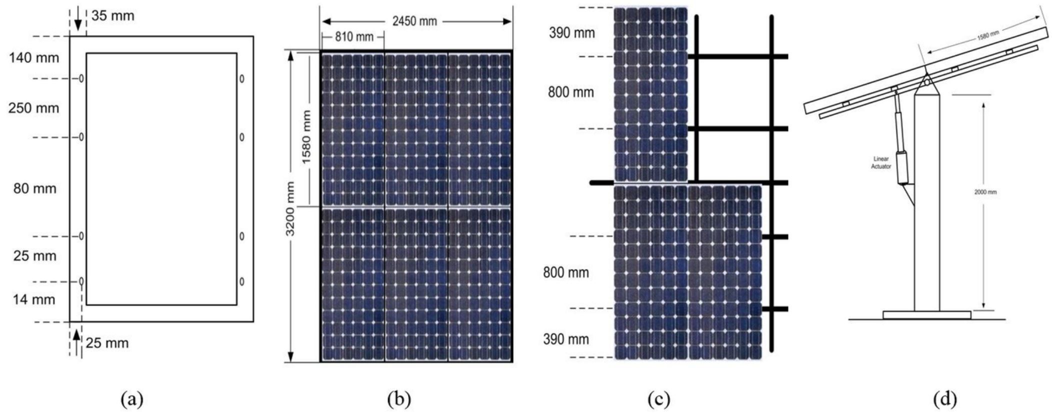

Figure 5: Mechanical design and models; (a) PV module dimensions, (b) platform design and dimensions, (c) mounting cage and installation model, (d) mechanical test design of the tracker

4 Electrical Design of Tracking System

The electrical design of the tracking system is comprised of an actuator control circuit, LDR resistors, angle sensor, real time clock, DC motor drive circuit and linear actuator. The control circuit includes the device that operates the linear actuator to get the platform to track the sun instantly. There are two different control devices implemented in this study, one of which processes the data obtained by LDR resistances located on the east and west sides of the platform. The measured data are compared to define the exact position of the sun. Although this controller is implemented and operated in a reliable way, the second controller is designed to eliminate LDR sensor dependency by using a real time clock that is synchronized with local hour. The key components of the control devices include angle sensor, real time clock (RTC), dc motor driver and the linear actuator. Since it is important to determine the exact position of the PV systems as well as the position of the sun, an angle sensor is required in the sensor-based controller designs. The MMA7361 angle sensor is used to measure the position of the PV systems. The angle sensor provides positional information on the X, Y and Z axes when the required supply voltages are supplied to it [24]. Position data can be directly obtained from the X, Y and Z outputs on the angle sensor as an analog value. Just the Y output is used in these outputs, since the sun tracking is carried out on a single axis. The angle sensor placed on the PV system transmits the analog value from Y output according to its position. The location where the PV system turned is determined after the position information is obtained and processed. The position information of the PV system is very important when determining the system position, westernmost and easternmost positions, and returning the PV system to the horizontal plane at night in order to balance the CG. The time and hour-based control device performs the tracking operation depending on the local time. Therefore, this controller requires an RTC integrated circuit to perform precise control. The DS1302 RTC of Maxim, which is capable of counting the year, month, day, hour, minute, and second data up to the year 2100, is utilized for this purpose. The auxiliary crystal oscillating at 32.768KHz ensures the precision timing of DS1302 RTC, and the data is stored in the static RAM which is 31 x 8 bytes addressed consecutively in the RAM address space. The accuracy of the clock is dependent on the accuracy of the crystal and the accuracy of the match between the capacitive load of the oscillator circuit and the capacitive load for which the crystal was trimmed [25]. In this study, the linear actuator is used to enable the movement of the PV system on the sun tracking system. Movement in the east-west direction of the PV system is achieved by the linear actuator moving back and forth. As with the DC motor, the bi-directional control of the linear DC actuator is provided by the directional change of the current. So the H-bridge is utilized to allow the actuator to move in two directions. The L6203 DC motor driver, which is used as the motor driver, has an H bridge within it. After the required supply voltages of the DC motor driver are supplied, the linear actuator is controlled back and forth by the control signals which are sent over the control element. The L6203 DC motor driver was chosen in this study for its easy control and the fact that it can withstand as much as 4A DC current flows [26].

The linear actuator is identical to the DC motor in terms of control, but the motor motion is linear, not

Table 2: Features of IP66 Class Linear Actuator

Parameter	Value
Load Capacity	8000N
Operating Voltage	24V
Working Noise	48dB
Speed	5mm/s
Operating temperature	-20C +40C
Limit Switch	Yes

circular. The supply voltage of 24 volts is required for operation of the linear actuator. As with DC motors, the speed control of the DC linear actuator can be adjusted by the voltage drop on it. The catalog data of the DC linear actuators used in the system are given in Table 2. The DC linear actuator is selected due to its 8000 Newton load capacity, low current drawing under loaded operation and suitable structure for outdoor use, low speed operation and low power consumption features.

5 Control Circuits Implemented

Two different control circuits are designed to operate the sun tracking system. The first control circuit is sensor based, using the LDR to determine the position of the sun, and the PV system is placed in the appropriate position. In the second system, a real time clock is used. Previously, the sun position information is determined according to the time, and then the PV system is to move according to the determined position. The hardware and algorithms implemented for both of the controllers are introduced in the following subsections.

5.1 Sensor based control circuit

The circuit schematic of the control circuit that provides control of the sun tracking system is shown in Fig. 6 as the implemented circuit. The PIC16F877 microcontroller of the microchip is used as the processor in the control circuit. The actual position of the sun is obtained by the LDR and the recent position of the PV module platform is obtained from the angle sensor. Afterwards, the determined position data are compared to move the platform to the required right angle. The linear actuator is tasked with moving the platform to the required direction, where the PV modules are located at a perpendicular position to the sun. The PIC16F877 microcontroller, which controls the sun tracking system, is preferred since it has eight analog-digital conversion channels, PWM signals can be generated, and it is easy to program, low-cost and very popular on the market. The sun must be tracked successfully to operate the tracking systems efficiently. Solar sensors or various solar sensitive circuit elements are used to follow the sun. The solar sensors sold on the market are very expensive [4]. Therefore, various solar sensor circuits are being built for sun tracking systems, using LDR circuit elements to cut sensor costs [3]; [8]; [12]; [13]. In this study, two LDRs were used to track the sun on a single-axis in east-west directions. The LDR is a circuit element whose resistance varies inversely with the amount of light incident on it. LDR is used to measure the amount of solar radiation by performing a voltage-divider connection. Thus, the amount of voltage on the LDR varies with the amount of light. The amount of voltage is interpreted by controlling the analog channels of the microcontroller. By comparing the amounts of light falling on the sensors, the position of the sun is determined.

5.2

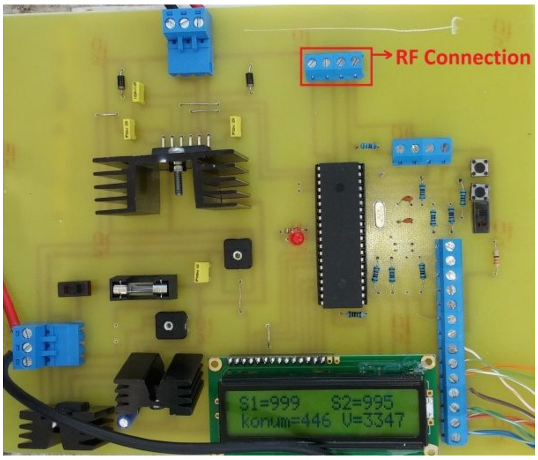

Figure 6: Sensor based control circuit

5.3 Time based control circuit

The sun tracker that is controlled with LDR data as sensor outputs operates efficiently on clear sky and sunny days. However, the control device underperforms on cloudy days and continuously searches the highest sun irradiation in east and west directions, leading to sensitivity and sudden changes on the mechanical platform. Thus, mechanical stresses on the base and energy consumption of the system are increased. Therefore, the sun tracking system is revised by designing a time-based control device. In such systems, the controller uses the predefined position and angle data of the sun [27]; [28]; [29]. In the implemented controller, the daily angles of sun are detected and are entered in the microprocessor of the control device. Thus, the position of the sun is compared with instant time provided by the RTC and sudden changes are prevented on cloudy days.

The implemented PCB of the device is shown in Fig. 7. The microcontroller used in this control device is also PIC16F877 as in the LDR based control device. The motor control of the linear actuator is performed by an L6203 motor drive device, and the angle is measured by an MMA7361 angle sensor, which is used to limit maximum tilt angles of the platform.

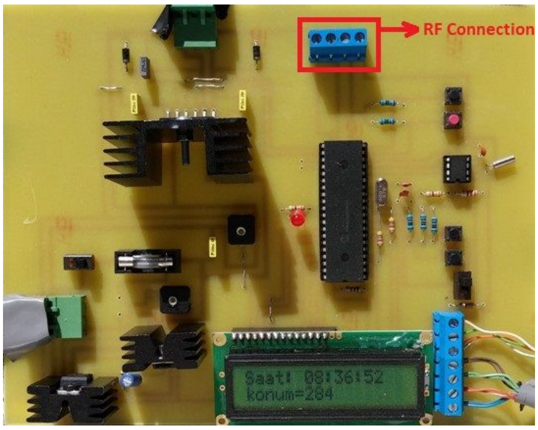

Figure 7: Time based control circuit

The solar angle data of the site where the tracker is installed are downloaded to the microcontroller as a database. Once the controller obtains the actual time from DS1302 RTC, it checks the tilt angle of the sun from the database corresponding to the defined time data. Then, the position data of the sun and angle of the platform are compared depending on the data obtained from the angle sensor. The controller starts to move the platform to match both these angles in order to bring the PV modules perpendicular to the sun. The flowchart of the time-based sun tracker is shown in Fig. 8. The first action on the control device is to adjust the date and hour.

Once the time adjustment is completed, the microcontroller detects the position and angle data of the sun and obtains the actual position of the tracking platform. Both sets of position data are compared to detect the difference, which is assumed as the error signal, with a view to clearing it. The actual position of the PV system is higher than the desired position obtained from the database, which means the PV system is further west than the sun and needs to be turned east to achieve the desired position. The PV system turns until the difference between the actual position and desired position is removed and the PV modules are located perpendicular to the sun. This type of control is tested for the same sun tracker system and it provided much more reliable and exact control of the platform.

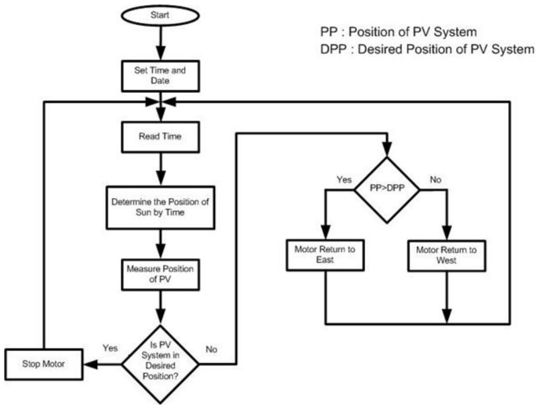

Figure 8: Flowchart of the time-based sun tracking system

6 Remote Monitoring Infrastructure of the System

Monitoring infrastructure and software are also implemented, to observe the operation of the sun tracking system. The communication device is designed with universal serial bus (USB) and wireless transmission features. The LDR outputs are measured and converted from the electrical signal to irradiation levels by a PIC18F4550 microcontroller calibrating the data. The microcontroller is capable of providing serial communication for low speed RS232 protocol and high-speed USB. The schematic diagram and PCB of the data acquisition card designed are shown in Fig. 9.a and Fig. 9 .b respectively. The transmitter and receiver of the wireless communication is constructed by a UTR-C12U transceiver that can be used as either a transmitter or receiver. The transceiver module provides frequency shift keying type modulation at 434 MHz communication band and provides high frequency stability against noise. The transceiver module is capable of modulating data at 2400 Baud-9600 Baud bandwidth, providing narrow band FSK. The modulation and demodulation of the transmitted data are performed with universal asynchronous receiver/transmitter (UART) protocol [30].

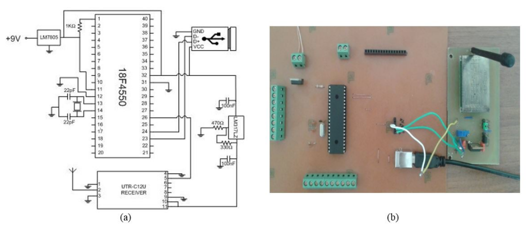

Figure 9: Data acquisition card, (a) schematic diagram, (b) PCB

The monitoring of the measured and calibrated data is performed by software that is coded as graphical user interface (GUI). The transmitted data is received on the USB connection and then stored in a database that is used to manage and process the sun tracking system data. The GUI screen is shown in Fig. 10 where the actual angle of the platform and irradiation data appear on the screen and a daily irradiation chart can be drawn. The interface software is coded using a C# software development kit that provides USB and UART connection protocols [31].

The measured position and irradiation data are stored in a database file for the purpose of analyzing the daily data, and in the case of any date picked on the calendar a graphical chart is generated by the designed software. The acquired data are instantly measured and the average of 10 minutes measurement is stored in the database. The daily irradiation charts as shown in Fig. 11 are drawn by using the average data in terms of hour-irradiation axes.

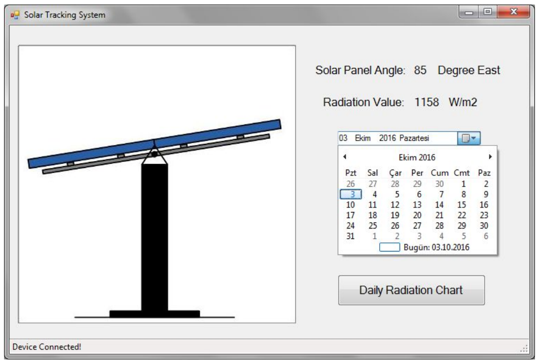

Figure 10: Graphic user interface of solar tracking system

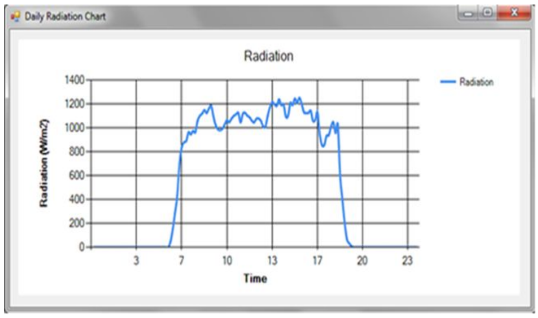

Figure 11: Daily radiation chart

The implemented GUI is intended to be improved with internet connection, to be converted into an online monitoring tool in future studies. The most recent view of the sun tracking system with its power conversion cabin and protection is seen in Fig. 12.

Figure 12: Sun tracking system in its site

7 Conclusions

The increased demand for energy generation and RES use is driving many areas of research and development. Solar energy plants are mostly installed as fixed bases. The disadvantages of fixed mounting are widely known by researchers familiar with solar energy research. It reduces the total energy yield of the plant, since it cannot track the daily movement of the sun. On the other hand, sun tracking systems that increase generated energy require additional mechanical and electrical calculations. In this study, a sun tracking system holding six PV modules of 200Wp each is modelled and implemented. The mechanical designs are tested and verified with computer aided design software. The latitude angle (φ), longitude angle (l), declination angle (δ), and hour angle (ω) of the site where the plant is to be installed are calculated and the mechanical calculations performed to improve the stability and reliability of the system. The electrical designs are focused on actuator control devices, sensor based and sensorless control, and remote monitoring applications. The LDR based controller device was produced at low cost, but the stability of the controller was not efficient. The controller structure was converted to a time-based system in the proposed studies. Its reliability was verified by the operation of the proposed controller on cloudy and less sunny days compared to the LDR based controller. Another contribution to the implemented system is the remote monitoring infrastructure, where the hardware and software are improved as introduced in the study. The GUI coded with C# software development kit is integrated with a database file that handles the daily irradiation data of the site for storage and analysis .

In future studies, the proposed communication and monitoring infrastructure is intended to be improved with an Internet connection, which will provide cloud storage and monitoring of the actual data.

7.1 Acknowledgements

This study is funded by Scientific Research Division (NEUBAP) of Nevsehir Haci Bektas Veli University with ref. NEUBAP14F11. The authors acknowledge NEUBAP Division for their support.

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