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Automatic Smart Solar Radiation Tracker for PV Power Plants

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Abstract— This paper concerns the automatic smart solar radiation tracker dedicated to photovoltaic panels. The proposed tracking system ensures optimum generation of electrical power by proper orientation of PV panels while consuming minimal energy. The design criteria are based on controlling the panel's position by automatic rotation throughout two DC motors only at certain times during the day. The followed methodology uses a microcontroller algorithm to redirect the solar panels in accordance with the actual coordinates of the sun. The idea is applicable to any PV system at any geographical location as panel rotation is changed according to the tilt and azimuth angles. This leads to capturing maximum radiation at any given time. Moreover, its power consumption is low due to its working mechanism and automatic sleep mode feature while not in use. Results have proved its cost-effectiveness, energy- efficiency, simplicity, and reliability in operation under different weather conditions.

Keywords: ***photovoltaic, solar cells, sun tracker, solar energy, tracking mechanism.***

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I. INTRODUCTION

The fact that conventional energy sources are unsustainable, environmentally harmful, and expected to diminish within a few years, placed deploying renewable eco-friendly energy sources at the center of public interest. "Solar energy is the cleanest and most abundant renewable energy source available. Solar energy is harnessed and converted into electricity using different technologies in which photovoltaic cells are the most popular and efficient one. Nonetheless, researchers are experiencing many challenges to optimize the efficiency of photovoltaic cells. According to a report published in 2019 by Fraunhofer Institute of Solar Energy Systems ISE, the maximum efficiency reached of a mono-crystalline and multi-junction cells are 26.7% and 46% respectively.

One of the main reasons for low-efficiency values is that the energy output of the PV cell is directly proportional to the sunlight concentration. PV power plant productivity is boosted when the solar panel is mounted perpendicularly to. Due to sun continuous position changing in the skydome, this orientation can only be achieved by implementing a movable tracker that follows the sun's position. In contrast, the absorption efficiency of an immobile solar panel would be significantly less. Researchers have compared the power output of a static solar panel to a one that has a tracking system and has observed improvement in efficiency by 40% on average. Thus, the solar tracking system comes into play to maximize the reception of sunlight by automatically altering the position of the solar module according to the sun incident on the earth at any time.

The sun's position can be determined by a combination of three different parameters; azimuth angle, altitude angle and GPS coordinates of the observer. The latter depends solely on the latitude and longitude of the site where the solar module will be installed. This parameter is constant and bonded to the geographical location. However, the other two parameters can vary at any instant caused by the earth's rotation around its own axis and earth orbiting around the sun. They can be imitated on the tracker by two rotations; vertical and horizontal. Researchers have employed different tracking mechanisms to harvest maximum sunlight.

A single-axis mode with tilted installation of the PV panels resulted in inaccuracy and less electrical output. Likewise, manually adjustment of the tilt angle seasonally to compensate for the absence of second axis tracker, lacks practicality and accuracy. Consequently, dual-axis autonomous tracker the optimum solution. The most popular technique is using light-detecting resistor (LDR). Although methodologies may differ in controlling strategy and/or sensors number and alignment, their theory is based on the same concept. Another approach uses small-scale photovoltaic cells to act as sensors, besides the main photovoltaic panel used to generate electricity. The abovementioned approaches will detect the sun's position very accurately and instantly. However, it will generate the electrical signals to rotate motors on the slightest light change causing extensive, sometimes unnecessary, energy depletion. This raises a question on they how to create a more energy-efficient and simple solar tracker.

The proposed design of sun tracker in this paper overcomes these disadvantages to eliminating the need for sensors, resistors, and the complexity, cost, and energy waste associated with them. Moreover, motors are limited number of rotations and a sleep routine feature are added for further energy savings. The Followed methodology uses a microcontroller algorithm to rotate the panels while maintaining a desired sun exposure. The system can be work at any geographical location, after a one-time setup, autonomously for the rest of its lifetime.

II. CHANGING THE POSITION OF PV ARRAY

The first step to fulfill the design requirements is to study the sun path. In order to obtain maximum sun coverage and minimum energy waste, the time frame between motors rotations has been carefully selected. Five cities were selected for altitude and azimuth angles analysis for their location's diversity with respect to the equator. In addition, the comparison was based on the different days of the year for all five locations, to cover all seasons, which are summer and winter solstices and fall and spring equinoxes, refer to Fig.1. It was found that every 30 minutes the percentage rate of change is 0.8% for altitude and 0.32% for azimuth. Furthermore, energy generation is not affected by angles deviation of within 3 degrees. Therefore, 30 minutes is selected as the motor's motion time intervals.

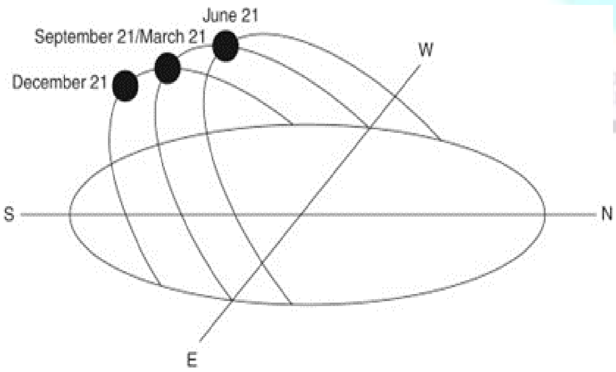


Fig. 1. Sun Path Changes over the year

For instance, using Jeddah, KSA coordinates, a chart showing the solar path over the whole year can be obtained as shown in Fig. 2.

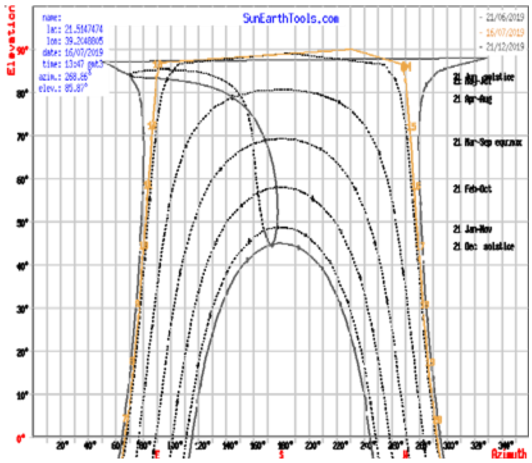


Fig. 2. Jeddah, KSA Annual Sun Path

III. SOLAR ANGLES AND LATITUDES

As mentioned earlier, in order to depict the sun's accurate position in the celestial sphere, three values must be known; GPS coordinates, altitude and azimuth angles. However, to facilitate a solar angles calculations variations over the day, further information should be known about declination angle and hour angle (APPENDIX).

A. Altitude angle

Altitude, also called elevation angle, donated by α, is the angle between the line to the sun's center and the horizon, as shown in Fig. 3. It starts with zero degrees at sunrise and increment gradually until it reaches the highest altitude at noontime. Then, it starts to decrement gradually until sunset. The mathematical expression of altitude as given:

$$Sin\,(Altitude) = sin\,(\delta) * sin\,(latitude) + cos\,(\delta) * cos\,(HA) * cos\,(latitude)$$

Where δ and HA are the declination angle and the hourangle respectively.

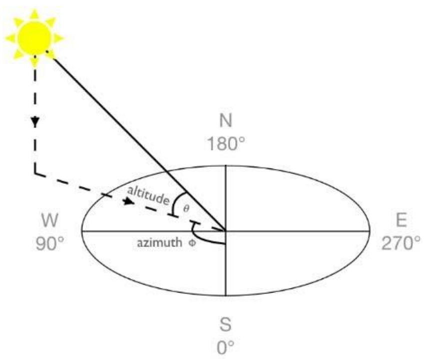


Fig. 3. Altitude and Azimuth Angles

B. Azimuth Angle

Azimuth is the angle measured clockwise between the north and the projection of the sun's radiations on the horizontal plane as shown in Fig.3. The values of the azimuth angle can be proven using trigonometric relations as:

*Cos (azimuth) = (sin (δ) * cos (latitude) - (cos (δ) * sin (latitude) * cos (HA))) / cos (Altitude)*

C. Noontime

Noon solar time is the time where the sun reaches its highest position in the sky. After noontime, the sun starts to descend to the west on its way towards sunset. The maximum value that altitude can have is 90 degrees if the zenith angle is 0 and the sun is directly overhead and perpendicular to the ground. However, the maximum altitude could be less than 90 depending on the season and geographical location. During summer, the sun will have a longer path in the skydome, which means higher maximum altitudes. On the other hand, during winter the sun path is shorter resulting in smaller than maximum altitudes. Noontime equation is:

*Noontime = (720 - (4 * longitude) - qtime) / 60*

Where qtime is the equation of time defined by the formula:

qtime = 229.18 * (0.000075 + (0.001868 * cos(y)) - (0.032077 * sin(y)) - (0.014615 * cos (2 * y)) - (0.040849 * sin (2 * y)))

Noontime is not only used to find the hour angle but also to find the precise motor angle. Equation (1) calculates the altitude from both east and west directions with no distinction, but the vertical motor does not recognize directions. Noontime value allows the mechanical system to move according to the directions by determining the correct motor angle.

D. Other variables

Additional parameters are do not contribute directly in the solar angles in calculations, yet they are vital for the system to operates a simultaneously with the Sunset time and Sunrise time. These parameters arise because day length varies depending on location and time of the year. The below equations are used to calculate sunset time and daylight hours;

$$\text{Sunset hour angle } \omega_s = \cos^{-1}(-\tan(\text{latitude}) * \tan(\delta)) \quad (6)$$

$$\text{Sunset time} = (\omega_s * 15) + 12 \quad (7)$$

$$\text{Day Light hours } DLh = (2 * \omega_s) / 15 \quad (8)$$

$$\text{Sunrise time} = \text{sunset} - DLh. \quad (9)$$

IV. DESCRIPTION OF THE PROPOSED TRACKER

A. Components

Electrical components used in this prototype are:

- Two identical DC servo motors, each of 5volts and 550mAmps.
- Arduino Uno board based on the ATmega328P controller.
- DS3231 I2C Real-Time clock
- Connecting wires between RTC and Arduino and between Arduino and both motors
- Mechanical Structure design aligns one motor vertically to reorient the panel toward the sun's elevation angle, and the other one horizontally to track azimuth angle as shown inFig. 4.

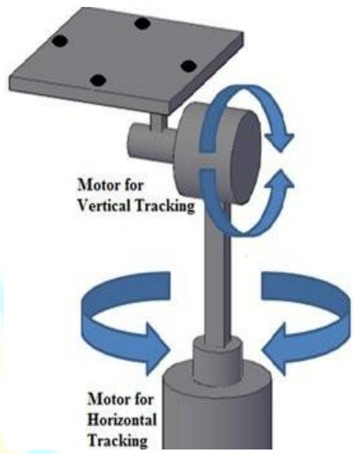


Fig. 4. Dual Axis Motos Rotation

B. Operation

A closed-loop control system controls the position of the solar panels by sending the control signals to the motors through Arduino UNO.

A main element in the system is a Real-Time Clock (RTC) that plays two important roles. First, it keeps track of the time and date, since this feature is not supported by Arduino UNO, to be used in hour angles calculations and to distinguish day from night. The Second, wake up source for Arduino from sleep mode every 30 minutes by executing an external interrupt time routine.

The end-user inputs latitude and longitude once in a lifetime. Users who have time zone different from the RTC time to their local clock time in hours, minute and seconds. These inputs are mandatory only once as long as the tracker is kept on the same location. The rest of all other instructions will be done without human intervention as long as its latitude, longitude and time have been set for the first time, the algorithm will be able to run. For example, in case the user is not using the solar panel for any reason, it can be simply disconnected and reconnected at any time and resume the operation normally without any further setup.

The day number is obtained automatically by the Arduino controller code every day or whenever the program is restarted. The code reads the date from the RTC and converts it into a number between 1 to 365, or 1 to 366 if leap year, January 1st is considered day number 1.

Time is a critical factor of the system to autonomously determine the working and sleeping hours. During the day, the code calculates azimuth and altitude angles twice per hour at equal intervals using (1) and (2). Instructions are to be performed not arbitrary but rather on specific times starting sunrise until sunset according to formulas (7) and (9).

After sunset, the vertical motor rotates the panel to be parallel to the ground, this position protects the solar panels from any wind that might occur in the night.

C. Flow Chart

The daily process starts by computing daily constant parameters enabling the program to determine what time is it and decide what to do and when. Next, the program runs one of two loops depending on the current time. There are two mains while loops, one for the daytime and one for the night. During the day loop, it finds solar angles every 30 minutes and initiate a signal to rotate the motors and continue sleeping for the rest of the time. During the night loop, controller is awakened every half an hour by the RTC interrupt routine, it checks the time, and if it is not sunrise yet, it goes back to sleep without executing any instructions. After sunrise, the process will repeat all over again. The flow chart illustrating the process is shown in Fig. 5.

Fig. 5. Process Flow Chart

V. ENERGY SAVING

Energy conservation is not only limited to restricted motors rotations, sensors and resistor discarding but also the sleep routine function of the microcontroller.

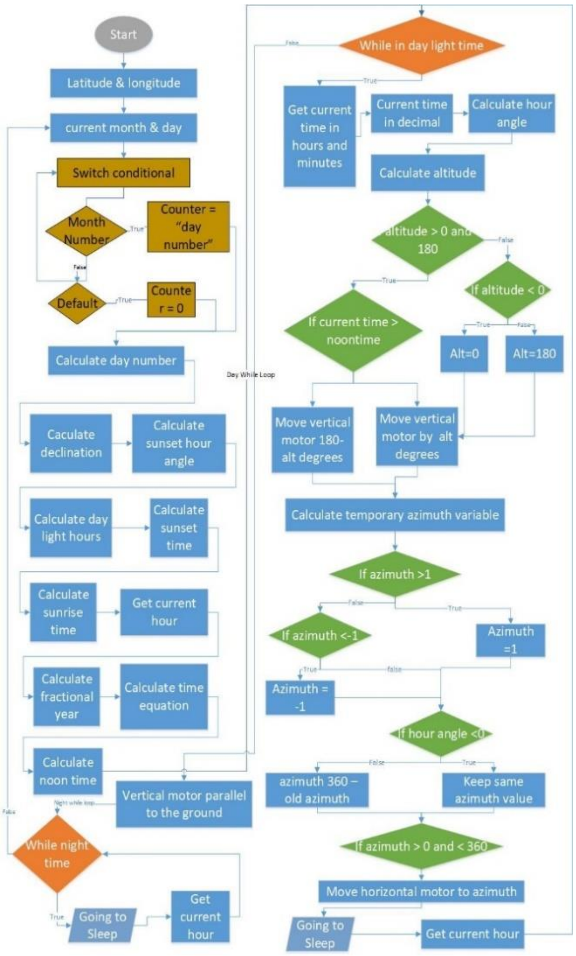
A. Motors Rotation

The motors will only rotate twice per hour during the day. The rest of the day and during the night, motors will be at complete rest and will not drain extra power. Unlike the sensor-based method that will activate the motors on the slightest light variation. The larger the PV power plant, the more power consumption of motors rotations.

Motors vary from one mechanical structure to the other according to the motor datasheet specifications. The exact energy loss caused by unnecessary motors rotations is difficult to be determined because the LDR based model depends on how often the motors will react to the sun's changing position.

B. Sensors and Resistors Exclusion

sensors, equivalent to 57.6W on an estimated daily average every five minutes. No sensors or resistors are needed no matter of the size of the PV power plant.



C. Controller Sleep Mode

Although the Atmega328P controller of Arduino consumes relatively low power, sleeping mode saves 90% to 93.3% of power. Atmega328P consumes 60mW of power at 5volts in active mode, while in sleep mode the current drops to 40uA at 3 Volts, and 60uA at 5 Volts, consuming 120uW and 300uW of power respectively. Among many sleeping modes with different characteristics and power-saving conditions, power down sleep is selected as it is one of the deepest sleeping modes and fulfill the design requirements.

VI. RESULTS AND OUTPUT

The proposed tracker is tested for different seasons of the year. To check results accuracy, the outcomes were compared against two references available online as software tools to find solar angles. The two references are not 100% matching. The data output was recorded for each day, city, and time separately, then the accuracy weighted and normal average was calculated. The results from the proposed tracker were matching the first reference by 95-97% and the second one by 93-97% for all five cities variables. The data statistics summary of code accuracy normal average for all cities combined against both references is shown in table I.

TABLE I. PERCENTAGE ACCURACY SUMMARY

Statistics	Reference 1		Reference 2	
	Altitude	*Azimuth*	*Altitude*	*Azimuth*
Normal Average	93.60%	98.10%	89.40%	96.70%
Standard Deviation	8.90%	3.70%	10.10%	5.50%

Table. II shows the weighted average accuracy compared to references for each city. The weighted average is based on the magnitude of the angles. The higher the magnitude, the more its weight.

TABLE II. WEIGHTED AVERAGE ACCURACY

Cities	Altitude Accuracy		Azimuth Accuracy	
	Ref 1	*Ref 2*	*Ref 1*	*Ref 2*
Jeddah	96.50%	98.60%	91.80%	97.10%
Nairobi	96.00%	86.40%	98.70%	96.50%
Melbourne	95.80%	92.00%	99.10%	93.70%
Frankfurt	93.80%	93.40%	98.20%	97.80%
Toronto	95.10%	96.40%	98.20%	98.70%
Total Weighted Average	**95.40%**	**93.40 %**	**97.20%**	**96.80 %**

The city of Nairobi solar angles have been tested as an example. Fig. 6 plotted these values in day time for each half an hour for 4 different days. It can be observed that the Fig. 7 is another representation of output angles versus references in the daytime for each half an hour for 4 different days of the year. The program was examined over the night and it found to be working properly. Fig. 8 is an Arduino screen output overnight for two consecutive hours. Fig. 9 is a sample of the Arduino screen display for the. The controller is interrupted twice per hour by RTC, executes the commands, goes back to sleep and so on.

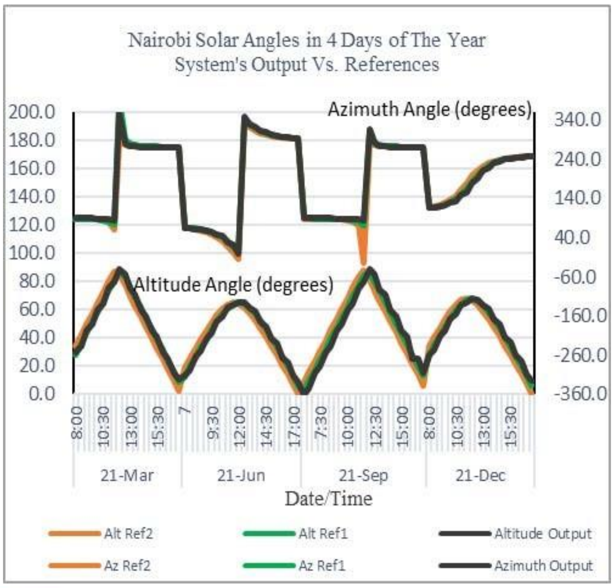


Fig. 6. Nairobi solar angles Output Vs. two references

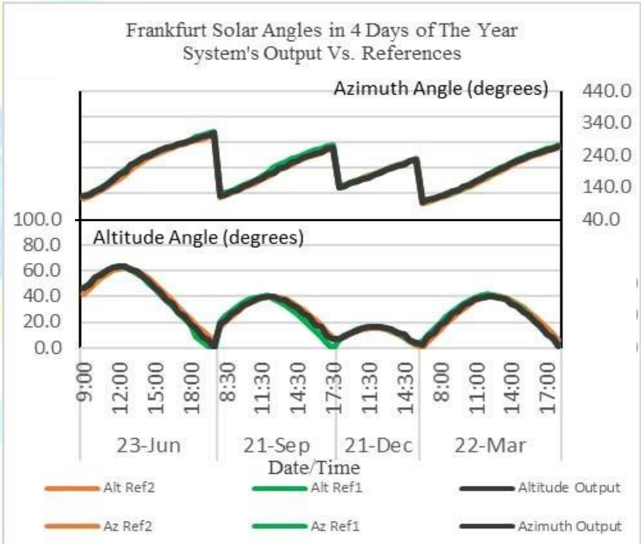


Fig. 7. Frankfurt azimuth angles Output Vs. two references

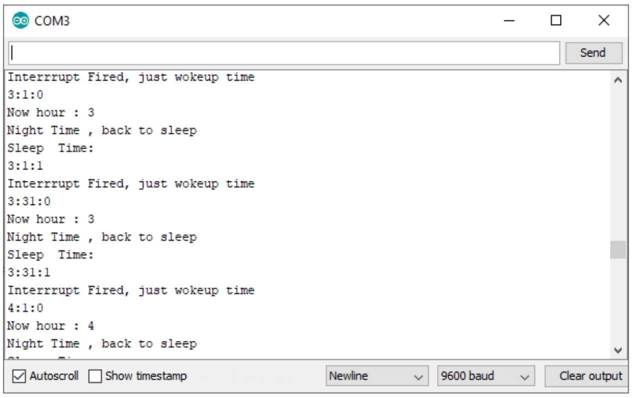


Fig. 8. Sleeping function overnight

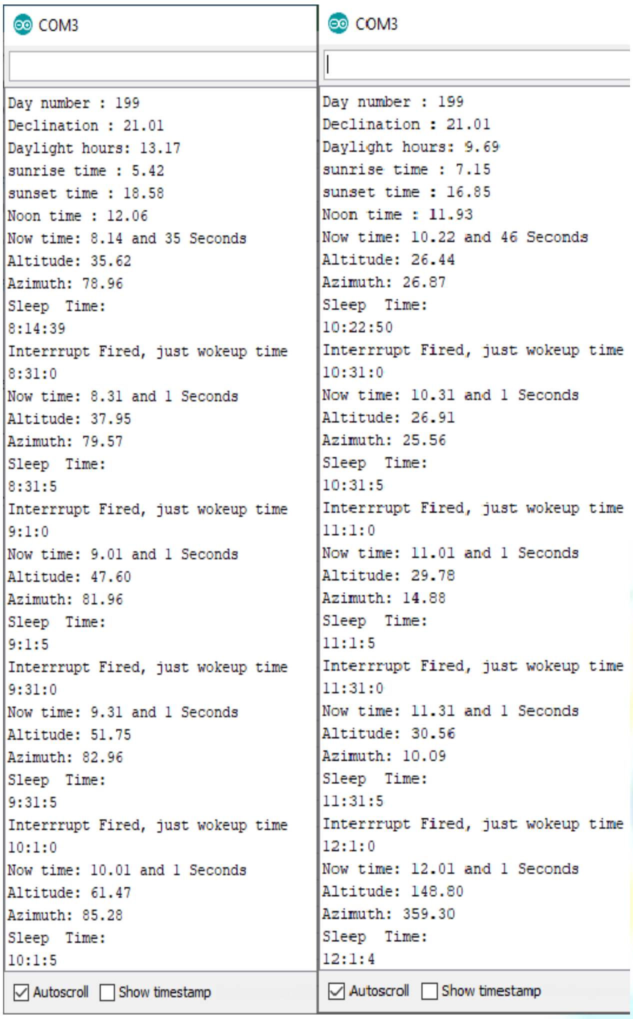


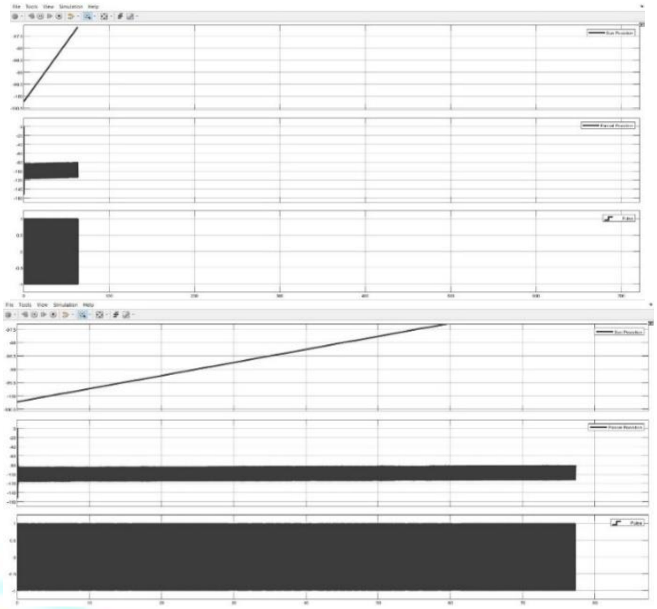
Fig. 9. Samples of Arduino Output

The commands executed every 30 minutes takes 4 seconds to complete. Daily constant variables also take 4 seconds, repeated once per day or on program restart. After that, the Arduino goes to deep sleep mode and is awakened by the RTC every 30 minutes and the procedure is repeated until sunset. In the course of nighttime, although Arduino continues to wake up every half an hour, it goes back to sleep without performing additional instructions until sunrise which takes 1 second.

Assuming September equinox, where day and night are equal in length, the microcontroller will work for 100 seconds during the whole day plus 24 seconds at night. Which means that it will work 0.0014% of the time in 24 hours. This percentage oscillates during the year according to the day and night lengths.

It is imperative to mention that the code is tested with extra commands to display results on the screen, taking more time to execute. In reality, these displaying functions are not needed and could be simply deleted or commented out taking less time and so save more power.

VII. RESULT



VIII. CONCLUSION

This paper presented the design, implementation, and testing of an automated dual-axis energy-efficient and cost- effective solar tracker. The proposed design cuts cost and complexity caused by conventional sensors-based trackers. Tracker will only follow the sun at predefined times to fulfill the main purpose of avoiding excessive energy waste, yet the desired energy output is obtained.

The sun tracker system has been implemented for Jeddah, Saudi Arabia area and tested for other four cities around the world; Melbourne Australia, Nairobi Kenya, Toronto Canada, and Frankfurt Germany. Results have proved its effectiveness, low cost, simplicity, reliability in different locations in addition to preserving energy.

Future researches can include wind direction and speed sensor to redirect the panels parallel to wind if it exceeded a certain speed and expected to damage the panel for extra protection of the panels. However, this needs further study nd analysis as it can cause lower energy output because the wind parallel position might not be perpendicular to the sun to harness maximum power.

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