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Design and Performance of an Automatic Solar Tracker Using GPS and Tilt Angle Measurement

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Abstract:

During recent years solar energy has been the most important renewable energy. Due to the Earth's rotation, the Sun rises and falls every day and its illumination angle changes continuously. PV systems equipped with solar tracker keeping solar cells directly facing the sun in real time is the best way to ensure the highest photoelectric conversion efficiency. In this paper a solar tracker system is proposed to increase efficiency and the ability of absorbing solar radiation of the photovoltaic module. An automatic designed system consists of GPS module, accelerometer for angle measurement, and a microcontroller which is responsible for the equipment management. The processing and control unit receives the current angle (feedback signal) and compare it to the desired angle from the database. If the difference between the feedback signal and the database angle is not zero, then the proposed system operates and fixes panels in optimum angle.

Keywords: Solar Tracker, GPS, MEMS Accelerometer, Photovoltaic power systems, Single-axis Tracker, Tilt angle, solar radiation, Energy efficiency.

۱. Introduction

Currently, solar radiation can be directly converted into useful energy through a variety of technologies. Due to the Earth's rotation, the Sun rises and falls every day and its illumination angle changes continuously. Rather than a fixed PV system, keeping solar cells directly facing the sun in real time is the best way to ensure the highest photoelectric conversion efficiency. Therefore the study of solar trackers has become a core search area in solar energy conversion technology. A solar tracker is a device that keeps solar cells facing the Sun at all times. The single-axis tracker follows the sun's east-west or north-south movement while two-axis tracker also follows the sun's altitude angle. Experimental studies have been performed to investigate the performance of various types of solar tracking system, including both open-loop and closed-loop type of schemes [۱۷]. For the open-loop tracking system, the tracker will perform calculation to identify the sun's position and determine the rotational angles of the two tracking axes using a specific sun-tracking formula in order to drive the solar panel towards the sun [۱-۳]. However, this automated system will stay operational even if the weather is cloudy and there is no sun visible to track, thus spending stored energy without any gain. The same issue arises when a clock mechanism is used for solar tracking with the help of stored parameters to compute the sun position angles. The angles are transformed to coordinates that drive the tracker [٤]. Another alternative is to have a database for the correct angle of incidence for the solar rays at a location stored and this stored data sets the solar collector position round the clock. Usually such systems are expensive and complex based on the requirement for the database storage media and clock accuracy. The open loop type is simpler and cheaper but it could not compensate for disturbances in the system and has low accuracy. On the other hand for the closed-loop tracking, the sun tracker normally sense the direct solar radiation falling on a photo-sensor as a feedback signal to ensure that the solar collector is tracking the sun all the time and keep the solar collector at a right angle to the sun's rays for getting the maximum solar insolation [٥-۱۰]. The closed-loop tracking mechanism has lower tracking error than open-loop tracking mechanism. However, closed-loop tracking mechanism is not reliable under foggy and cloudy weather conditions. [۱۱-۱۳]. ۲۰۱۰, Bajpai P, and his partner, Design, and Test Performance of an Automatic Two-Axis Solar Tracker System, [۱۷] and ۲۰۱۰ md.-tanvir arafat khan and his partner describes a microcontroller based design methodology of an automatic solar tracker [۱۸], Proposed method, the failure is "Parasitic" situations, such us partial cloudy weather, or accidental shading of different causes of the one or both sensors, which give errors . In this paper open-loop solar tracker system is proposed to increase efficiency and the ability of absorbing solar radiation of the photovoltaic module. An automatic designed system consists of GPS module, accelerometer for angle measurement, and a microcontroller which is responsible for the equipment management. The processing and control unit receives the current angle (feedback signal) and compare it to the desired angle from the database. If the difference between the feedback signal and the database angle is not zero, then the proposed system operates and fixes panels in optimum angle. Method in this paper is more reliable because finding the optimum angle dos not depend on the weather situation. In addition the sensor used in this method has high accuracy and low cost. Since this is a dual axis accelerometer, it can be easily applied to a dual-axis solar panel.

٢. Investigation of Best Tilt Angle for Optimum Solar Energy Harvesting

The energy generated from solar cells is proportional to the amount of incident light. It reaches its maximum value when the solar cell is perpendicular to the sun's rays [١٩]. The solar radiation on an inclined surface is a function of the sun's ray (*IN*), and some related angles, as described in Fig. ١ [٢٠]. The incident solar energy over tilted surfaces is estimated as in the following steps:

٢.١. Basic Idea

The conventional orientation strategies imply to tilt the PV panels with a daily-based angle ($S=٠$, $S=\Phi$, or $S=\Phi$ δ), where δ can be calculated using the following equation [٢١]:

$$\delta = ٢٣.٤٥^{\circ} \sin [٣٦٠(٢٨٤ + n)/٣٦٥] \quad (١)$$

This research proposes an improved strategy for best solar energy harvesting. In this strategy, the tilt angle has been calculated for each day to achieve the maximum incident solar energy over the PV panels during this day for the site under study. Then, these angles have been formulated in an empirical formula for easy and efficient use of the proposed strategy at different sites.

٢.٢ .Calculation of The Radiation at Different Tilt Angles:

The average daily radiation on a horizontal surface ($\bar{H}$), can be expressed by defining K_T, the fraction of the average daily extraterrestrial radiation (H_o) as [٢١]:

$$\overline{K_T} = \bar{H} / \bar{H_o} \quad (٢)$$

Then, the average daily radiation on a tilted surface $\bar{H}_T$ can be expressed as:

$$\bar{H}_T = \bar{K}_T \times \bar{R} \quad (٣)$$

Where,

$$\bar{R} = \left(١ - \frac{\bar{H}_d}{\bar{H}}\right) \times \bar{R}_b + \frac{\left(\frac{\bar{H}_d}{\bar{H}}\right)(١ + \cos S)}{٢} + \frac{\rho(١ - \cos S)}{٢} \quad (٤)$$

$$\frac{\bar{H}_d}{\bar{H}} = ١,٣٩ - ٤.٠٢٧ \times \bar{K}_T + ٥,٥٣١ \times (\bar{K}_T)^٢ - ٣.١٠٨ \times (\bar{K}_T)^٣ \quad (٥)$$

$$\bar{R}_b = \frac{\cos(\emptyset - S) \times \cos\delta \times \sin\omega_s + (\pi/١٨٠) \times \omega_s \times \sin(\emptyset - S) \times \sin\delta}{\cos\emptyset \times \cos\delta \times \sin\omega_s + (\pi/١٨٠) \times \omega_s \times \sin\emptyset \times \sin\delta} \quad (٦)$$

$$\omega_s = \cos^{-١}(-\tan\Phi \times \tan\delta) \quad (٧)$$

$$\omega'_s = \min[\omega_s, \cos^{-١}(-\tan(\Phi - S)\tan\delta)] \quad (٨)$$

$\bar{H}_T$ has been calculated at different tilted angles: *S* has been swept to identify the value that achieves the maximum collected $\bar{H}_T$ every day: Sweeping of *S* starts from -٩٠° up to ٩٠°—including $S=٠$, $S=\Phi$, and $S=\Phi-\delta$. Fig. ٢ shows the flowchart for achieving the above addressed methodology. [٢٢]

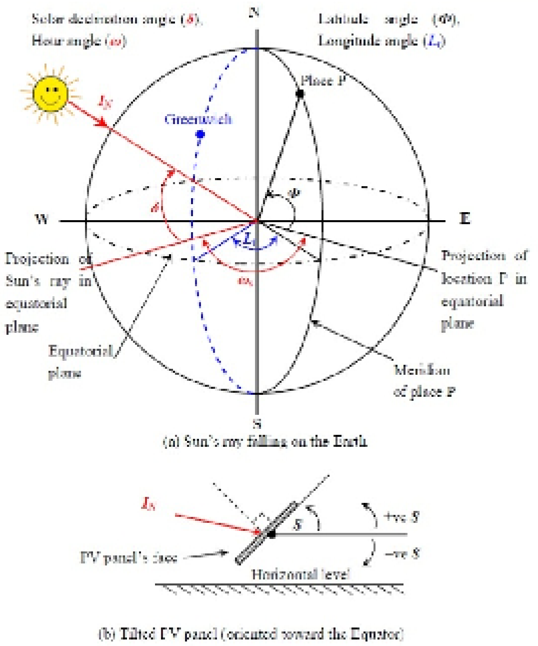


Figure ۱ Solar radiation tracking concepts

۳. Case Study

۳.۱. Description of the PV Plant

The PV plant has been installed on campus Shahid Chamran university of Ahwaz-Iran. The ۱۱۰ photovoltaic modules composing the field are oriented south .Each string is made of ۱۱ series connected ۱۸۵ W Solar photovoltaic modules .The main characteristics of the modules are listed in Table ۱.

Table ۱ ۱۸۵ W module

Technical Data	STP۱۸۵S-۲٤/Ac
Open - Circuit Voltage (Voc)	٤٥.۰ v
Optimum Operating Voltage (Vmp)	۳٦.٤ v
Short - Circuit Current (Isc)	٥.٤۳ A
Optimum Operating Current (Imp)	٥.۰۹ A
Maximum Power at STC (Pmax)	۱۸٥ Wp
Operating Temperature	-٤۰°C to +۸٥°C
Maximum system voltage	۱۰۰۰ V DC

The ۱۰ strings are subdivided into two groups of five strings. Each group is connected to the inverter input stage. Each inverter is endowed with Maximum Power Point Tracking (MPPT) systems; each inverter has a three phase AC output, our research done on one of the power inverters. The inverters electrical data are reported in Table ۲. The monitoring of the photovoltaic plant is made by using two different data loggers one is dedicated to the climate data, while the second one is used to record the electrical data.

Table ۲ inverter electrical data

Technical Data	۱۲۰۰۰TL
Rated power (@ ۲۳۰ V, ٥۰ Hz)	۱۲۰۰۰ W
Nominal AC voltage	۳ / N / PE; ۲۲۰ / ۳۸۰ V
AC power frequency / range	٥۰ Hz, ٦۰Hz / -٦ Hz … +٥ Hz
Max. output current	۱۹.۲ A
Max. efficiency	۹۸.۱ % / ۹۷.۷ %
Operating temperature range	-۲٥ °C … +٦۰ °C

۳.۲ Description of Automatic Solar Tracker System

۳.۲.۱ Schematic Arrangement

The goals of the proposed automatic solar tracker are generation an input signal using an automatic system (GPS), generation a feedback signal indicating tilt angle of the solar panels, and providing a human user interface in order to response to the user's commands and reporting the panels angle. In the proposed system, an input unit which is formed by a GPS system sends an input signal containing time information to the processing and control unit. The processing and control unit receives the information and compare them to its database. The database consists of a table containing the desired angle of the panels at particular days and months of the year in the PV power planet location. If the angle of the panels is different from the desired angle, the processing and control unit rotates the motors in a suitable direction. While the motors are rotating, the feedback unit provides a signal containing angle of the panels. The processing and control unit receives the current angle and compare it to the desired angle. If the difference between the feedback signal and the database angle is zero, the motors are stopped.

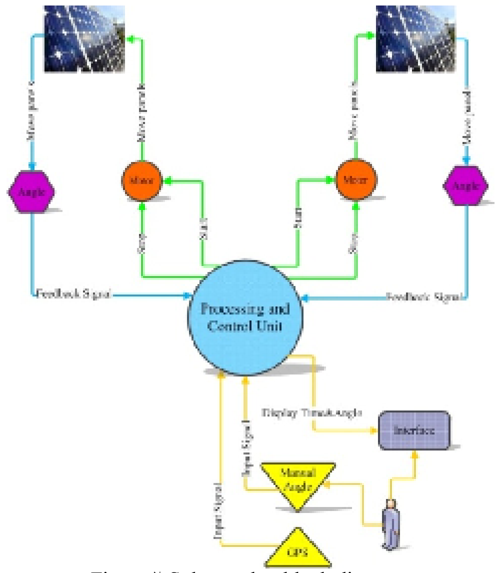


Figure ۲ Solar tracker block diagram

۳.۲.۲ Sensor System Used in the Control Circuit

In order to measure the angle of solar panels, the MEMS accelerometer"ADXL۲۰۲" is used. This low cost sensor measures positive and negative acceleration to ۲g. As the accelerometer measures static acceleration, it can be used as a tilt or angle sensor.

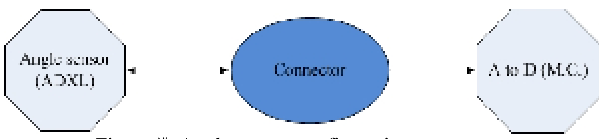


Figure ۳ Angle sensor configuration

The analog output of the accelerometer is converted to duty cycle modulated (DCM) digital signal via an output circuit. Nominal output of ADXL۲۰۲ is:

"۰ g = ۵۰% Duty Cycle"

"Scale factor is ۱۲.۵% Duty Cycle Change per g"

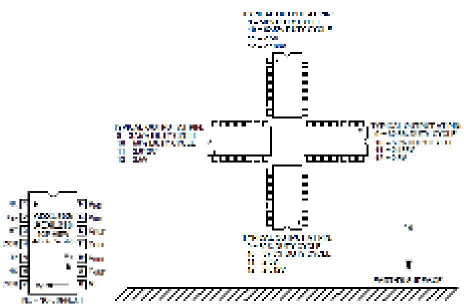


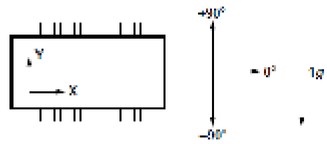
Figure ٤ Sensor response due to earth's gravity

Figure ۳ shows sensor response due to earth's gravity force which "۹" and "۱۰" are axes x and y duty cycle output pins. For example for axis x, output duty cycle equals to ٦۲.۵% and acceleration is +۱g. So relationship between output duty cycle (D.C.) and measured acceleration is linear and equals to:

$$\%D.C. = \%۱۲.۵ * (acceleration) + \%۵۰ \quad (۹)$$

۳.۲.۳ Angle Measurement Using ADXL

One of the most important accelerometer sensors is tilt and angle measurement. Accelerometers determine orientation of an object using gravity force as an input vector. When accelerometer sensitive axes are parallel to the earth's surface, they have the most sensitivity to tilt, and it can be used as a tilt sensor.



X AXIS ORIENTATION TO HORIZON (°)	X OUTPUT: X OUTPUT (g)	X OUTPUT: Δ PER DEGREE OF TILT (mg)	Y OUTPUT (g): Y OUTPUT (g)	Y OUTPUT (g): Δ PER DEGREE OF TILT (mg)
–90	–1.000	–0.2	0.000	17.5
–75	–0.966	4.4	0.259	16.9
–60	–0.866	8.6	0.500	15.2
–45	–0.707	12.2	0.707	12.4
–30	–0.500	15.0	0.866	8.9
–15	–0.259	16.8	0.966	4.7
0	0.000	17.5	1.000	0.2
15	0.259	16.9	0.966	–4.4
30	0.500	15.2	0.866	–8.6
45	0.707	12.4	0.707	–12.2
60	0.866	8.9	0.500	–15.0
75	0.966	4.7	0.259	–16.8
90	1.000	0.2	0.000	–17.5

Table ۳ x & y outputs VS changes in angle

Table ۱ shows changes in x and y outputs VS changes in the angles mentioned in the table. So:

$$acceleration = A\sin(angle/۱\ g) \quad (۱۰)$$

So:

$$angle = \sin^{-۱}(acceleration/A) \quad (۱۱)$$

The relationship between duty cycle (D.C.) and angle in degrees equals to:

$$angle = \sin^{-۱}((\frac{D.C. - ۵۰\%}{۱۲.۵})/A) \quad (۱۲)$$

Where (A) is a scale factor. ADXL in addition duty cycle output, provides an analog output via a low pass filter, which can be converted to digital form using an analog to digital converter simply.

٣.٢.٤ Automatic Solar Tracker Controller

In conventional methods the operator had to push a button of each month to change the angle of the panel. But here in this project in addition to the manual mode. We have designed an automatic mode that is made by using by using GPS module and RTC IC (real time clock) .the principles of GPS and RTC and how we have used them in this project be explained in the following parts.
In this system RTC IC calculates the exact date and time by using its circuit and shows it on the LCD. There is also a GPS system on the board (its function is explained in the following parts). Here we use GPS to make sure that we always have the right time and date. Finally the time and date that the RTC shows will always be calibrated by using the time and date that the GPS gives us.
Here one of the advantages of using GPS is that we don't need an operator to set time and date. The correct final date and time will be used to set the panels on the right angles (according to the program that is saved on the microcontroller memory). The designed board has the capability to be developed. Besides time and date also geographical characteristics of the place can be received by using the GPS.

٣.٢.٥ Motor Driving

In order to move panels and fix them into the desired angle, some mechanical arms are used that are controlled by two AC electric motors. Each motor is controlled by two relays, one rely is used to rotate the motor clockwise, and the other one is used to rotate the motor anti-clockwise. A micro controller generates the control signals and determines which relay should be active and run the motor in the correct direction. The digital part of the driver and the high voltage part are isolated by optocouplers to prevent damages in micro controller circuit.

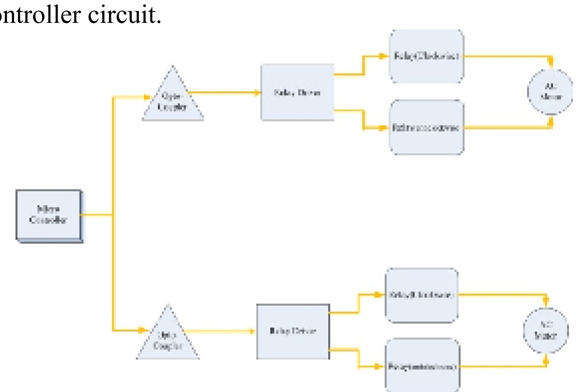


Figure ٥ Motor driver block diagram

٣.٢.٦ Angle Control Function

After calculating time by GPS, the goal angle will be determined by comparing the database existing in the internal micro controller memory. The current angle of panels is read from ADXL and it compared to the set point value in degrees. The sign of the error determines that if the motors rotate clockwise or anti-clockwise. If the value of the error is less than a specific value, the panels are fixed to the desired angle.

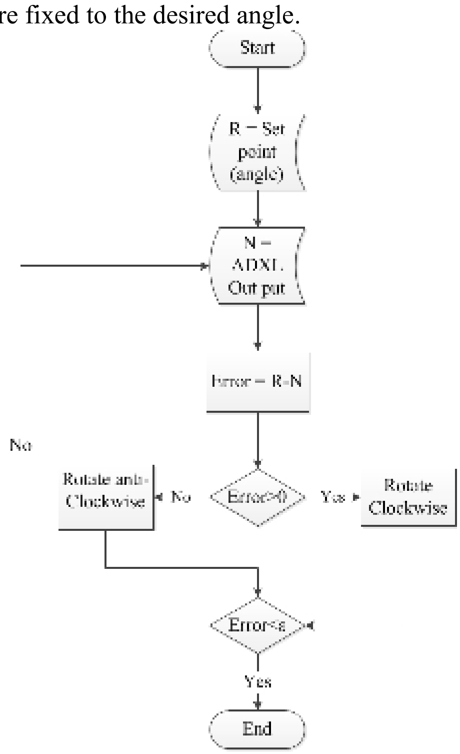


Figure ٦ Angle control flowchart

٣.٢.٧ The Function of RTC (Real Time Clock):

We can use the internal RTC of the microcontroller to make a digital clock. But the main problem is that when the power of the circuit is cut of the clock goes off. If you want to make a microcontroller on for all the time you can use a backup battery. Here we use a DS١٣٠٧ IC. It has also a calendar besides the clock. Here we can use a ٣volts back up battery, which is able to operate ١٠ years.

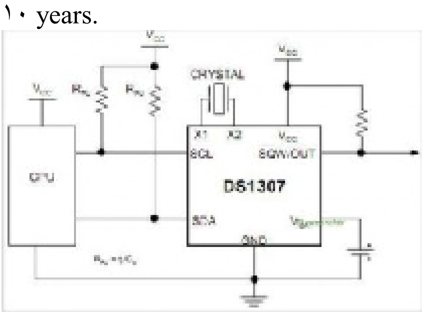


Figure ٧ RTC schematic diagram

۳.۲.۸ The Function of the GPS Module:

GPS module receives the data lines from the satellites by using an antenna. Then it takes the date and time out of these lines (by using the codes in microcontroller). Then we can use date and time as mentioned before.

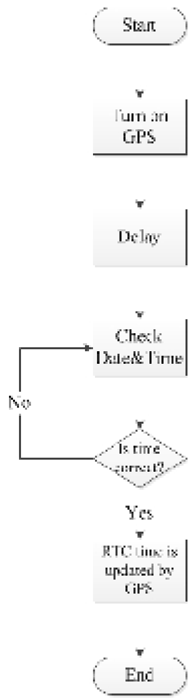


Figure ۸ GPS function flowchart

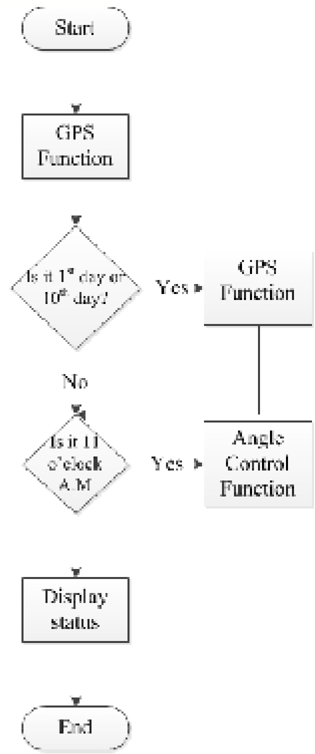


Figure ۹ Main flowchart

٤ Conclusion

This research proposed an improved strategy for best solar energy harvesting. In this strategy, the tilt angle has been calculated for each day to achieve the maximum incident solar energy over the PV panels during this day for the site under study. It is possible to track the Sun position using a database containing an optimum angle for each day or month, a low cost accelerometer for tilt angle measurement, a GPS and a real time clock (RTC), and a microcontroller which is responsible for the equipment management. This method can replace the light dependent resistors. Especially large PV areas can benefit by this solution, replacing a large amount of sensors with only one microcontroller to control all the modules. "Parasitic" situations, such us partial cloudy weather, or accidental shading of different causes of the one or both sensors, which give errors While the proposed method in this paper is more reliable because finding the optimum angle does not depend on the weather situation. In addition the sensor used in this method has high accuracy and low cost. Since this is a dual axis accelerometer, it can be easily applied to a dual-axis solar panel.

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