

Electronic system for improvement of solar plant efficiency by optimized algorithm implemented in biaxial solar trackers

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Abstract — In this paper it is described an algorithm, implemented in a biaxial solar tracker, that can instantly calculate the sun position at the latitude and longitude of a set point. The algorithm can drive up to two engines which are able to change the position of a solar panel, in order to increase its efficiency, for tracking the sun in its movement from east to west (azimuth motion) and in its elevation up to solar noon (tilt motion). The whole system is adaptable to various types of structures as it involves a cycle of self-learning of the structure and consequently the adaptation of calculations to the tracker on which it is installed.

Keywords – solar panel, solar tracker, azimuth motion, tilt motion

I. INTRODUCTION

A solar tracker is a mechanical device which is able to favorably move to the solar rays a photovoltaic panel, a solar thermal panel or a solar concentrator. The main purpose of a tracker is to maximize the efficiency of the device hosted on board. In a photovoltaic field the modules installed on a tracker are usually arranged geometrically on a single panel in order to avoid the use of a tracker for each module. According to their design features solar trackers are classified according to: their degrees of freedom, the type of power supply provided by orientation mechanism and the type of electronic control. Solar trackers are able to offer to the panel a single or dual axis freedom of movement. Among one degree of freedom trackers, can be mentioned:

- Tilt (i.e. pitching) trackers which are the easiest to implement; they rotate around east-west axis (X axis). The panel is raised or lowered (usually manually twice a year) toward the horizon so that the angle to the ground is statistically optimal according to the seasonality. In practice, a tilt tracker is made using telescopic mechanical profiles in order to raise or to lower the solar panel respect to the horizon. Conceptually similar to the lifting shelf of a school desk these trackers offer a production increase of less than 10% that doesn't justify a servomechanism.

- Roll trackers are designed to “follow” the sun across the sky in its daily journey regardless the season of use. In this case the rotation axis is north – south axis (Y axis), while the height of the sun above the horizon is ignored. These trackers are suitable for low-latitude countries (including Italy, especially in the south) in which sun path is larger, on average, during the year. The required rotation to these structures is wider than the tilt, sometimes going up to $\pm 60^\circ$. These trackers make each row of photovoltaic modules appears as a spit oriented toward the equator.

- Tracker azimuth (i.e. yaw) have a degree of freedom with zenith – nadir axis (Z axis). To achieve this, the panel is mounted on a turntable servo, flush to the ground. The resulting increase in electricity production is approximately 25%

The most sophisticated trackers have two degrees of freedom, by which they are able to perfectly align, in real time, the orthogonal of solar panels with solar rays. These trackers have guaranteed an increase of electricity production up to 35%-40%, even if they are characterized by a more complex design. Tracking systems of biaxial trackers can be astronomical, i.e. driven by a software that calculates instantly the sun position and moves the panels accordingly (as the algorithm presented in this paper) or light-sensitive cell, capable of moving the panels towards the strongest light source (sun) in every single moment.

On the basis of power required for the movement, the trackers can be divided into active, if set in motion by motors, or passive, when set in motion by independent physical phenomena as thermal expansion of gas, etcetera. The active trackers can be classified by the type of electronic control which drives the movement: in the analog type the control is generated based on information of a sensor that detects the position of the brightest point in the sky while in the digital case the control comes from a microprocessor which, through special stored tables, knows in every moment the position of the sun in the sky.

This type of driving, used in the electronic system described in this paper, ensures greater productivity, especially in the days of low solar radiation



Figure 1. A biaxial solar tracking

II. CALCULATION OF SUN POSITION

In order to calculate the solar radiation on a plane of the Earth surface, the relative position of the Sun on the celestial sphere and the plan coordinates have to be known. The position of the sun is defined if the reference system is specified. The position of the Sun relatively to a point on Earth is given by the solar height angle α and by azimuth angle γ . The solar height or solar altitude (α) is the angle formed by the direction of the solar rays (those ones directed towards the Earth) with the horizontal plane (horizon). The azimuth angle or solar azimuth (γ) is the angle between the projection on the horizontal plane of the solar rays and the south; it is positive if the projection falls to the east (before the solar noon) and it is negative if the projection falls to the west (after noon); it may vary between 0° and $\pm 180^\circ$.

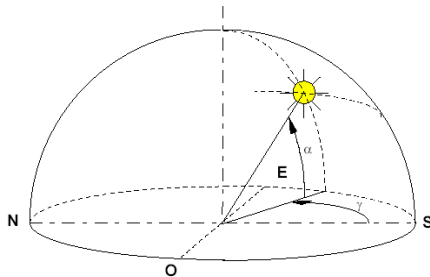


Figure 2. Solar height angle (α) ed azimuth angle (γ)

These two angles depend on declination of solar rays δ , latitude φ and hour angle ω . The declination is the angle formed by the inclination of solar rays (determined by the sun-earth line) and the equatorial plane. Its variation is from $-23^\circ 27'$ in winter up to $23^\circ 27'$ in summer. The declination for each day of the year can be determined by the Cooper formula:

$$\delta = 23,45 \sin[2\pi(n+284)/365] \quad [\text{degrees}]$$

where n represents the number of the progressive day starting from January 1.

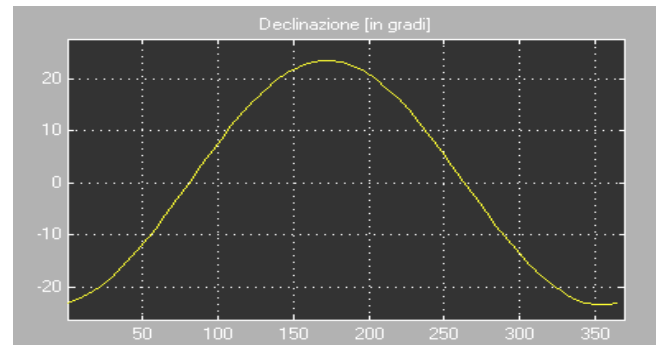


Figure 3. Trend diagram of solar declination

Latitude φ is the angle between the line joining the observation point and the equatorial plane. It takes values from 0° at the equator up to 90° at the North Pole and -90° at the South Pole. The hour angle ω is the angle between the projection of the line joining the centers of gravity of the sun and the Earth on the equatorial plane and the reference (Greenwich) meridian. It takes values between -180° and 180° by varying 15 degrees per hour; it is 0° at solar noon. The instant position of the sun can thus be determined by the following formulas:

Solar angle (or solar height or Tilt):

$$\alpha = \arcsin(\sin\delta \cdot \sin\varphi + \cos\delta \cdot \cos\varphi \cdot \cos\omega) \quad (1)$$

Azimuth angle:

$$\cos\gamma = [\sin\alpha \cdot \sin\varphi - \sin\delta] / (\cos\alpha \cdot \cos\varphi) \quad (2)$$

III. DEFINITION OF THE ALGORITHM

Following parameters are defined:

- n : number of the progressive day starting from January 1.
- h_{conv} : conventional or legal time
- h_{sol} : local solar time (different from National solar time)
- δ : declination
- φ : latitude
- L : longitude (positive from Greenwich meridian to East) up to 180°
- ω : hour angle

A. Calculation of declination:

$$\delta = 23,45 \sin[360 \cdot (n+284) / 365] \quad [\text{degrees}]$$

B. Calculation of solar time of sunrise and sunset equating to zero the equation (1):

$$\sin\delta \cdot \sin\varphi + \cos\delta \cdot \cos\varphi \cdot \cos\omega = 0$$

The hour angle from sunrise to solar noon (or symmetrically from solar noon to sunset) is determined:

$$\omega = \arccos(-\tan(\delta) \cdot \tan(\varphi))$$

sunrise time is: $ha = 12 - (\omega/15)$

sunset time is: $ht = 12 + (\omega/15)$

C. Calculation of sun position:

To calculate the position of the sun on a day n at hour h is necessary to know the latitude and longitude of the installation site.

D. Hour angle determination at generic time:

$$\omega = 15^\circ \cdot h_{sol} - 180^\circ \text{ [degrees]}$$

The local solar time determination is made taking into account two corrections: the first is the actual solar noon of the place than the one at reference meridian time zone, the second adjustment includes the calculation of a term called “equation of time” that takes into account the anomalies in the Earth orbit.

$$h_{sol} = h_{conv} + (Et - 4 \cdot (Lmr - Lp))/60, \text{ where}$$

h_{conv} is the National solar time (not the legal time), Lmr is the longitude of the reference meridian of the time zone (for Italy it is 15° East), Lp is the place longitude.

It should be underlined that generally the solar time does not coincide with the civil time. Indeed, a solar day is the time interval during which the Sun appears to have completed a cycle around a stationary observer on Earth. This does not correspond exactly to the time required for one complete rotation of the Earth around its axis: the length of day varies, slightly, during the year. If an observer facing the equator triggers a timer at midday, that is when the Sun center is located on the plane containing the meridian and the Earth center, after a few days, at 12.00 o’ clock, measured by the timer, the Sun is not in the plane of the meridian, but passes through it before or after. This difference (equation of time) is caused, as already noted, by the anomalies that characterize the Earth orbit. Et is variable and fluctuates during the year since, as said, the speed of the earth around the sun is not constant throughout the year. The value of the correction can be calculated by the following formula:

$$E_t = -10.1 \text{sen} \left(360 \frac{2n_g + 31}{366} \right) - 6.9 \text{sen} \left(360 \frac{n_g}{366} \right)$$

and displayed in figure 4.

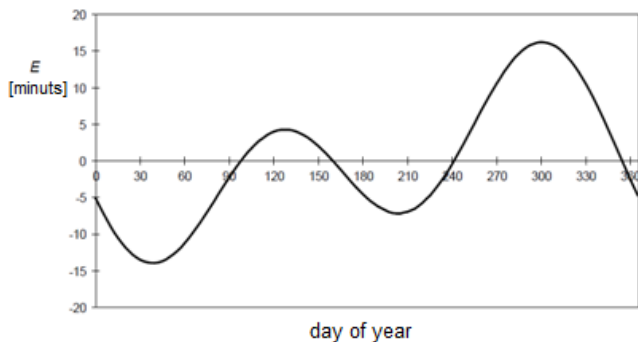


Figure 4. Equation of time

Known declination, hour angle and latitude, the sun position in the various instants of the year is given by:

Solar angle (or solar height or Tilt):

$$\alpha = \arcsen(\text{sen}\delta \cdot \text{sen}\phi + \text{cos}\delta \cdot \text{cos}\phi \cdot \text{cos}\omega)$$

Azimuth angle:

$$\text{cos}\gamma = [\text{sen}\alpha \cdot \text{sen}\phi - \text{sen}\delta] / (\text{cos}\alpha \cdot \text{cos}\phi)$$

IV. SOLAR TRACKER ARCHITECTURE

A simplified block diagram of the solar tracker architecture object of this paper is shown below.

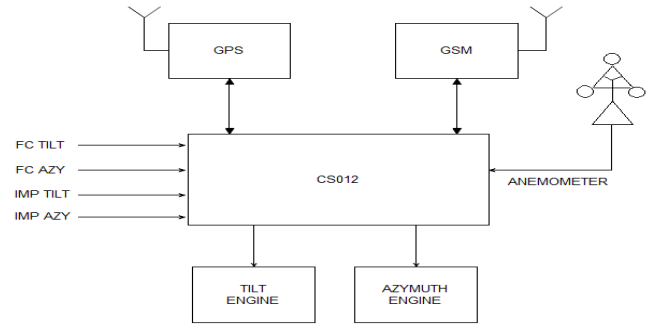


Figure 5. Solar tracker block diagram

The designed electronic board CS012 is the heart of the system: a picture of the board is shown in figure 6 and a simplified block diagram is shown in Figure 7. The board drives two motors (tilt and azimuth engines) capable of orienting a solar panel for tracking the sun in its movement from east to west (the azimuth motion) and in its elevation up to solar noon (tilt motion). Using an anemometer, the board makes the whole structure is protected from sudden gusts of wind, disabling the movement of the panel. It is connected to a GPS position detector that provides the latitude and longitude of the installation place of the structure and a GSM communication module that transmits alarms or system malfunctions.

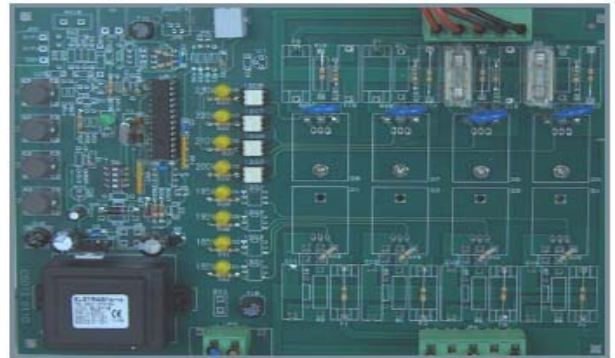


Figure 6. The electronic board CS012 implemented in SMD technology

The heart of the electronic CS012 is represented by a microcontroller, the PIC16F876 from Microchip, in which the algorithm for calculating the position of the sun, in C code, is implemented. The board is also equipped with a stabilized power supply circuit, an RS485 data port to interface it with an external PC (in order to program the PIC using MPLAB programmer), four configurable limit switch inputs and two power outputs to drive the engines .

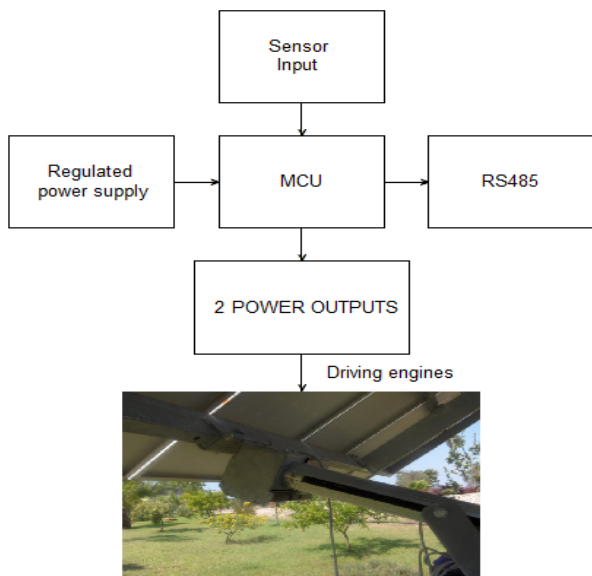


Figure 7. Block diagram of CS012

V. PROCESS FLOW CHART

In this section is reported the flow chart relative to the operations carried out, step by step, by the electronic board managed by the PIC that drives the engines of the Solar tracking system. After a preliminary phase of acquisition of the GPS coordinates (latitude and longitude) and a scan of the structure (limits self-learning of the structure) there's the acquisition time phase and the check if it is greater or less than the sunrise time. If yes, the process continues with the calculation of daily parameters such as solar declination, equation of time, etc., necessary for the calculation of the parameters α and γ relative to the position of the sun. Then there is the execution phase of the two engines, and then the check whether sunset time is reached. If so, before returning to the stage of acquisition time, there is the east positioning of the structure.

VI. SYSTEM ADVANTAGES AND ACCURACY

Compared to other solar tracking systems currently on the market, which usually use light sensors, the solution presented in this paper, using GPS position detector, avoids maintenance problems (for instance there is no need about cleaning or calibration checking of light sensors) and allows a significant reduction of power consumption since in systems with light sensors the engines are forced to move continuously in order to find the point of maximum light intensity. On the basis of experimental results from photovoltaic implants in which the realized solar tracking systems are installed (figure 9), the electronic board CS012, throughout the entire day, ensures high accuracy (typically less than 1%), in the handling of the PV solar panel, due to the algorithm for calculation of sun position implemented through Matlab software and then converted into C language in order to be installed on the microcontroller. It should be underlined, however, that the accuracy of calculation can be affected by the complexity of the entire mechanical structure which includes the solar panel and the solar tracker

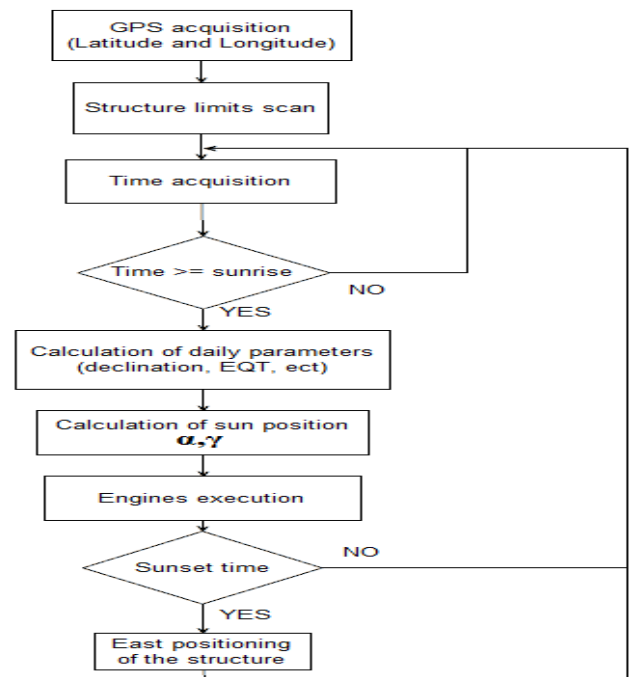


Figure 8. Solar tracking system flow chart



Figure 9. Photovoltaic panel with solar tracking system

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