Design and performance evaluation of a solar tracking panel of single axis in Colombia

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ABSTRACT

This paper presents the mechanical design of a single axis solar tracking system, as well as the electronic design of a system that to record in real time the electric power delivered by the solar tracker and to evaluate its performance. The interface was developed in Labview and it compares the power supplied by the tracker with the power supplied by static solar panel of the same characteristics. The performance is initially simulated using Pv-Syst software, and later validated with the data obtained by the interface. As a result, the use of the solar tracker increases the power delivered by a minimum of 19%, and it can go as high as 47.84%, with an average in increase in power of 19.5% in the monthly energy production. This experimental result was compared with the simulation by Pv-Syst software and shows a difference of only 2.5%, thus validating the reliability of the simulation. This behavior pattern coincides with previous studies carried out for equatorial latitudes.

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1. INTRODUCTION

The use of solar energy to generate electricity through photovoltaic systems has had an unprecedented worldwide development in the last 10 years [1]. This development has resulted from different aspects among which we can highlight the maturity of the technology and the need to respond to global warming [2, 3] leading to international agreements for the reduction of CO2 emissions, and therefore, in development plans and economic incentives provided by some governments [4, 5]. When fixed solar panels are used to capture the energy from the sun, they do not make the best use of the resource because during the course of the day the sun's rays will not always be perpendicular to the plane of the panels, and thus, their production is reduced. To respond to this phenomenon, the option of using solar trackers is presented [6, 7].

Solar trackers are mechanical devices which orientate the panels to remain as perpendicular as possible to the sun's rays during the day, following the solar trajectory from sunrise to sunset [8]. Several researches have studied the energy efficiency of these trackers and compared their efficiency with relation to fixed panels [9]. In the University of Salvador designed in 2012 a solar tracking system with two axes, which had two photoresistences located in the panel to find the angle of incidence of light. The unbalance of the signal from these sensors is sent to a comparator circuit, periodically activated by a PLC, to start an electric motor and a linear actuator, both of 12 volts, locating the solar panel at their corresponding angles. Finally the energy generated in the panels is directed to a charge controller PHOCOS CX-40 to be stored in batteries of 6V [10]. In [11] a conducted a performance comparison between an inclined fixed photovoltaic system and a dual-axis solar tracker, the data was collected for one year between two identical 7.9 kW photovoltaic systems with the same modules and inverters installed at the Mugla University. At the end of the study, it was calculated that the dual-axis tracking system obtained 30.79% more energy than the fixed system.

Turrillas [12] performed a MATLAB simulated comparative study of energy efficiency in solar trackers as a degree project at the Public University of Navarra-Spain. The project compared fixed systems with single and dual axis tracking systems. The simulations show that the single-axis and dual-axis tracking systems obtain an improvement of 30.41% and 39.35% in the energy production yield compared to the fixed photovoltaic system. On the other hand, in [13] implemented an automated solar tracking system based on the PIC 16F84 microcontroller, which controlled an angular positioning motor. The motor used was coupled to a gear of a rotational axis that allowed the displacement of the panel. The single-axis tracker achieved approximately a 14.7% increase in solar energy production.

In the Technological University of Pereira-Colombia, carried out the project "Design and implementation of a solar tracker for the optimization of a photovoltaic system" in 2010. This design focuses on a single-axis tracker that uses a 12-volt step motor controlled by a MC68HC908GP32 microcontroller based in the data obtained from two luminosity sensors [14]. The total energy delivered by the photovoltaic modules found in the bibliography can be validated by specialized simulation software, such as Pvsyst [15]. This software of recognized solvency, can designe residential and industrial photovoltaic systems [16]. The energy variables of the system, especially those related to the solar panels, can be calculated with the help of the climatic data of the place where the photovoltaic arrangement is intended to be simulated [17].

This article is organized as follows. The first section describes the solar tracking system and explains concepts about the movement of the sun, azimuth angle, solar time and the angle of inclination of the tracker. The second section presents the mechanical design of the single-axis tracker, as well as the controller designed for the perpendicular tracking of the sun in Colombia. Then, the efficiency and energy production of the solar tracker and the fixed module are compared, and the theoretical results obtained through the PVsyst software are contrasted against the experimental results obtained with the LABVIEW interface, named MPUNAB.

2. MATERIALS AND METHODS

2.1. Solar tracking system

2.1.1. Solar time

Normally, in the daily life the civil hour is used; this lasts 24 hours and was created to allow the communities of the same zone or country to drive the same hour. However, a solar day lasts a little more than 24 hours, and this excess makes that between the civil hour and the solar hour exists a considerable difference of minutes. To calculate the solar time, it is necessary to use the equation of time ET in minutes, shown in (1); where d is the angle of deviation according to the consecutive day of the year N and is calculated through the (2). Assuming N=1 as the first of January and N=365 as the thirty-first of December [18, 19].

$$ET = 9.87\, sin(2d) - 7.53\, cos(d) - 1.5\, sin(d) \quad (1)$$

$$d = \frac{360}{365}(N - 81) \quad (2)$$

From the expressions (1), (2) the solar time TS is determined by (3), where TC is the local time.

$$TS(hora) = TC - \left(\frac{ET}{60}\right) \quad (3)$$

2.1.2. Relative position of the sun with a point on Earth

To determine the location of the sun with respect to a point on earth, two angles are used: the height, which is the angle of the sun with respect to the horizontal plane; and the azimuth, which is measured in a clockwise direction from the south to the projection of the sun in the horizontal plane as shown in Figure 1. The value of the altitude and azimuth angles is a function of the time, day of the year and latitude of the place, and can be calculated through numerical methods [20, 21]. First, the angle of declination of the Earth

(Γ) caused by the translation movement is determined from (4), where N is the consecutive day of the year to be known.

$$\Gamma = 23.45 \sin\left[(284 + N)\left(\frac{360}{365}\right)\right] \quad (4)$$

The hour angle (hs) is the angle between the local meridian and the time of study, i.e., the angle formed between the solar noon hour and the reference time. The hour angle is obtained from (5), where TS is the solar time determined in (3). Figure 1 shows a graphical representation of the relationship between the path of the sun, the height of the sun and the azimuth angle with respect to the coordinates of a reference.

$$hs = 12 - TS * 15 \quad (5)$$

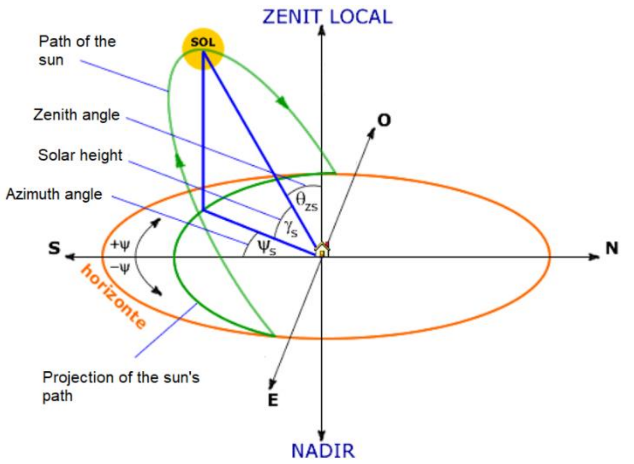

Figure 1. Location of the sun with respect to the earth

With the (4), (5) and the latitude (L) in which the solar panel will be located, it is possible to determine the height of the sun h.

$$\sin(h) = \cos(L)\cos(\Gamma)\cos(hs) + \sin(L)\sin(\Gamma) \quad (6)$$

The azimuth angle of the sun is given by (7)

$$\sin(\psi_s) = \frac{\cos(\Gamma)\sin(hs)}{\cos(h)} \quad (7)$$

When the azimuth angle is greater than 90° (when the position of the sun exceeds the axis or vertical east-west plane), an inverse function must be applied under the following reasoning:

$$\cos(hs) > \frac{\tan(d)}{\tan(L)} \rightarrow \psi_s = \sin^{-1}\left[\frac{\cos(\Gamma)\sin(hs)}{\cos(h)}\right] \quad (8)$$

$$\cos(hs) < \frac{\tan(d)}{\tan(L)} \rightarrow \psi_s = 180 - \sin^{-1}\left[\frac{\cos(d)\sin(hs)}{\cos(h)}\right] \quad (9)$$

2.1.3. Single-axis horizontal solar tracker

This solar tracker rotates on a horizontal north-south axis and the photovoltaic panel is located parallel to the axis of rotation. The trajectory drawn is always an arc from east to west perpendicular to the horizontal plane, which differs from the solar trajectory in the inclination it presents. The angle of inclination can be determined from (10). Figure 2 shows how the control angle (ϕ) varies with respect to the time of day (hs) and the day of the year (N).

$$\phi = \tan^{-1}\left(\frac{\tan(h)}{\sin(\psi_s)}\right) \quad (10)$$

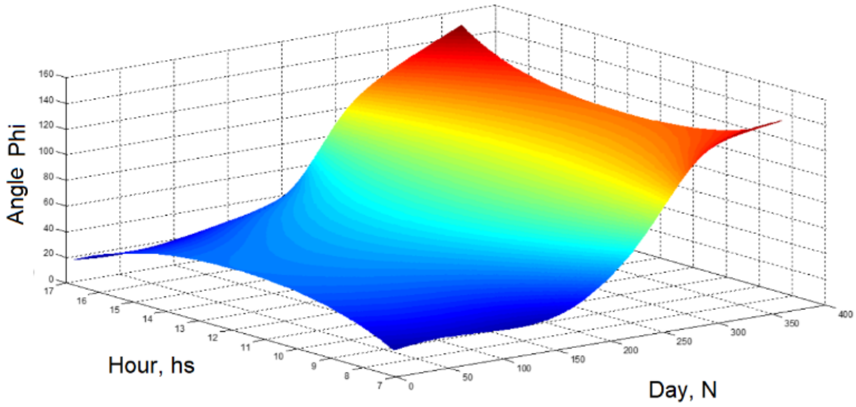

Figure 2. Angle ϕ vs. hour and day of the year

2.2. Solar tracker design

The structure was designed to support a photovoltaic panel with dimensions $1650\ mm \times 990\ m \times 40\ mm$ and an approximate weight of 19 Kg. The material selected for the structure was made completely of aluminum due to the corrosion resistance when working outdoors, the low weight, and the avoidance of corrosion by galvanic coupling with the aluminum panel frame. The base is made of aluminium tubes with a rectangular profile and dimensions 3"× 1,5". Regarding the electrical characteristics of the photovoltaic panel used in the tracker, these are presented in Table 1.

Table 1. Electrical characteristics of the photovoltaic panel

Electrical specifications	Value
Standard test conditions rating (STC)	250 watts
PV USA test conditions rating (PTC)	226.2 Watts
Max. power voltage (Vmpp)-STC	30.4 Volts
Max. power current (Impp)-STC	8.24 Amps
Open circuit voltage (Voc)-STC	38.4 Volts
Short circuit current (Isc)-STC	8.79 Amps
Max. system voltage-STC	600 Volts
Module efficiency-STC	15.3%

2.2.1. Mechanical design

An electric linear actuator is used for the movement of the solar panel, in conjunction with a crank-wheel-centred slide mechanism as shown in Figure 3. The actuator modifies the length RCB and the dot C represents the starting point of the piston travel in the actuator. The angle ϕ represents the angle of inclination of the photovoltaic panel, and the length RBA represents the length of the crank. The value of the link Rc, which enables the panel to be manipulated between angles of 0° to 180°, is given by (11). Knowing the distance that the actuator stem must travel to obtain the control angle, the value of RCB can be determined according to (12).

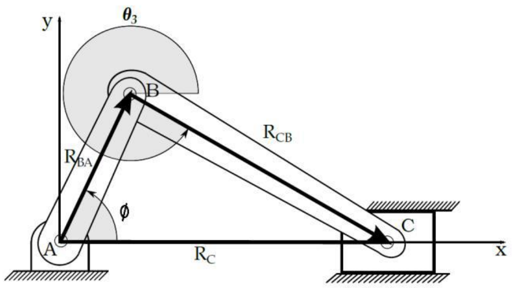

Figure 3. Mechanism of twist crank-connecting-sliding

The mechanism is a fast return, causing that when approaching the 180°, small changes in the travel of the actuator quickly change the rotation angle of the panel. The graphical representation of (11) can be seen in Figure 4. The linear section of the actuator is between the ranges of 0° to 150°, therefore, the mechanism will be limited to work in these ranges to facilitate the position control of the panel.

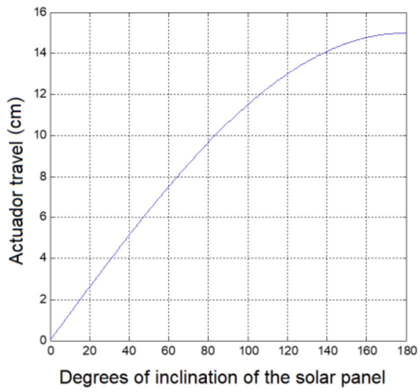

Figure 4. Panel rotation angle vs. actuator travel

The value of the link Rc that enables the panel to be manipulated between 0° and 180° is given by (11). Knowing the distance that the actuator stem must travel to obtain the control angle, the value of RCB can be determined according to (12). The mechanism is of fast return, causing that when approaching 180°, small changes in the travel of the actuator quickly change the rotation angle of the panel. The graphical representation of (11) can be seen in Figure 4. The linear section of the actuator is in the range of 0° to 150°, therefore, the mechanism will be limited to working in this range to ease the position control of the photovoltaic panel.

$$R_C = R_{BA}\cos(\phi) + \sqrt{(R_{BA})^2\cos^2(\phi) - (R_{BA})^2 + (R_{CB})^2} \tag{11}$$

$$R_{CB} = \frac{(R_{BA})^2 - 2\phi R_{BA}R_C + R_C^2}{\sqrt{R_{BA}^2 - 2\phi R_{BA}R_C + R_C^2}} \tag{12}$$

In order to analyze the displacement that the structure could suffer due to the wind, an evaluation was carried out with the finite element method (FEM) of Solidworks. The nominal speed reference was assumed as 20 m/s, a higher value than the maximum speed registered in 5 years by a meteorological station located on the site where the solar tracker will be placed. From this data, and based on the decree 1400 of 1984 (Colombian Code of seismic-resistant constructions) [22], the wind pressure on a structure is determined by the (13), where Vm is the wind speed expressed in Km/h, and H is the height above the ground of the structure.

$$P\omega = 0.005Vm^2\left(\frac{H}{10}\right)^{\frac{2}{7}} \tag{13}$$

For a height of 31.5 meters a wind pressure of 35.97 ⁄m2 is obtained. By simulating the structure in SolidWorks it is obtained that the maximum displacement by frontal winds is 0.1776 mm and 1.243 mm for side winds. The aluminum did not exceed its elastic limit (34.5x106 N⁄m2); with frontal winds the tension was 7673,9 N⁄m2 and for lateral winds it was 25612,57 N⁄m2. It should also be noted that the structure of the tracking system operates from 0° to 150° in order to control the position of the panel, since the linear section of the actuator is within this range.

2.2.2. Electronic system

The data processing and the control algorithm of the system is programmed in an Arduino UNO R3. The selected linear actuator is a LINKAN A/C LA32 which speed is regulated with a PWM signal. For the power stage is used the shield for the Arduino Pololu dual VNH5019 that operates between 5.5 and 24 volts, and supports a current of 12 Amp. To record the data, the Arduino Xd05 shield is used, which has a real time clock that provides hour, minutes and seconds, and day, month and year; data needed to calculate the solar time. For the feedback of the panel positioning is used a linear potentiometer BOURNS mark 5 K, powered at 3.3 V.

Due to the noise present in the feedback signal, a Butterworth digital low-pass filter is implemented with a system sampling period of 5.56 ms and a cut-off frequency of 3 Hz. This type of filter has the characteristic of flattening the signals with few undulations in the passing band. The transfer function of the system is observed in (14).

$$G(z) = \frac{0.002554z^2 + 0.005109z + 0.002554}{z^2 - 1.852z + 0.8622} \tag{14}$$

2.2.3. Control system

For the position control of the solar tracker a discrete Proportional Derivative controller is used, (15), since it allows a quick response to small changes in the process variable when it is close to its set point, avoiding the dead zone of the actuator.

$$G(z) = 2.5 + 0.5(1 - z^{-1}) \tag{15}$$

Evaluating the controller's response, the system reacted to changes in the reference signal, observing a stable state error of 2° caused by the dead zone of the motors and a setting time of 5 seconds, to bring the panel from 60° to 150°. For levels of reference close to 150°, the response is not adequate, this is due to the non-linear behavior of the system in this region, as observed in Figure 5.

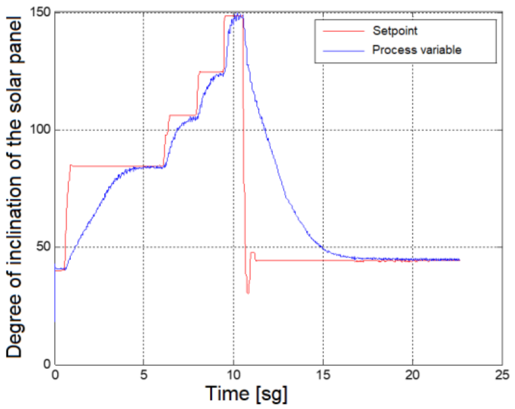

Figure 5. Transient response of the position control of the solar panel

The general logic with which the system operates, complies with the following protocol: first, the control angle is determined from the equations listed in section 2, then the PD controller adjusts the position of the photovoltaic panel, for which a time of one minute is set, after this time the control signal is sent to zero and fifteen minutes later the process repeats. At night the panel is placed in a resting position to avoid wind loads. The logic was established with the objective of reducing the energy consumption of the actuator.

2.2.4. MPUNAB monitoring system

For the monitoring of the energy supplied by the panels, an LABVIEW interface was designed. This interface helps to define which of the two alternatives is more suitable, according to the output power. The data acquisition board selected is the National instruments DAQ 6008, it has four analog inputs, each one with positive and negative input identification to facilitate the reading of the negative analog voltages. The current sensor selected is the non-invasive TED GX 201-CT sensor that delivers a voltage proportional to the magnetic field induced by the current passing through the phase of the inverter. A 220 VAC to 6 VAC low power transformer is used to condition this voltage to the data acquisition card. The LABVIEW interface, named MPUNAB, monitors all the components of the power delivered by the inverter: frequency, power factor, active, reactive and apparent power.

To validate the data obtained by the MPUNAB interface, the information obtained is compared with the DAVIS weather station data, which is property of the Autonomous University of Bucaramanga. The comparison is made between the solar radiation obtained from the weather station and the power delivered by the photovoltaic panel with the help of the MPUNAB interface. This graph can is shown in Figure 6. From the Figure 6 it can be seen that the data obtained from the interface is similar to the data obtained by the weather station. Therefore, the interface can be used to obtain reliable data for this article.

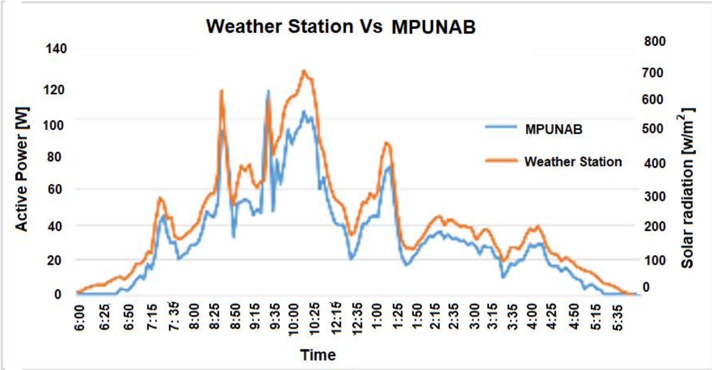

Figure 6. Meteorological station vs static panel

3. RESULTS

Figure 6 shows the generation power curves of the fixed panel vs the solar tracker in relation to the hours of the day; this was obtained through PVsyst software simulation. The power rising time to the maximum peak in the fixed panel is slower, which reveals that a large part of the direct radiation from the sun is not being received by the panel, thus, the energy production is lower. On the other hand, the power rising time to the maximum peak for the tracking panel is much shorter due to the perpendicular movement of the panel with respect to the sun's rays. The difference in energy production between the solar tracker and the fixed panel is 276 Wh/day. This result takes into account the energy consumption of the solar tracker control system. According to this simulation, about 20% more energy is expected to be obtained with the solar tracker. This value is determined by calculating the difference between the area under the curve of the tracker and the fixed panel, shown in Figure 7.

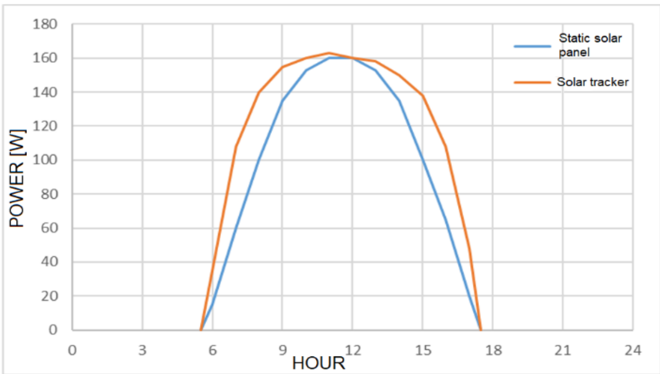

Figure 7. Simulation of produced energy, solar tracker vs static panel

To calculate the increase in electrical power delivered by the tracker panel (Pottracker) over the fixed panel (Potfixed) the (16) is used. Figure 8 shows the results of the evaluation of the efficiency of a solar tracker based on the curves described in Figure 7.

$$Eficiencia = \frac{(Pot_{Seguidor} - \mathrm{Pot}_{Estatico})*100}{Pot_{Estatico}} \quad (16)$$

The curve of increase in the electrical power by the use of the solar tracker is shown in Figure 8; the validation of these results obtained with the simulation in PVsyst was done through the MPUNAB interface. A continuous monitoring was conducted over a period of 2 months, which allowed to compare the energy produced by the solar tracker and the fixed panel. The data obtained reflects continuous disturbances such as clouds and, in some cases, rain. This response is reflected in Figure 9, where it can be seen that from early hours in the morning the tracker produces more electrical power than the fixed panel; similarly, the continuous disturbances in the incidence of solar rays are also perceived. Calculating the increase in the electrical power of the solar tracking over the fixed panel, (16), it is obtained the increase in energy shown in Figure 10.

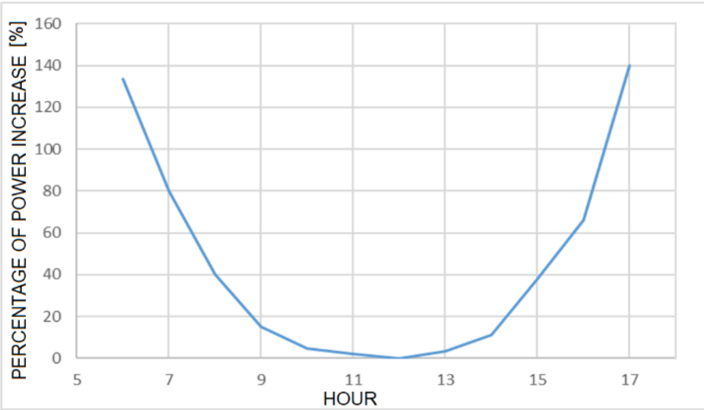

Figure 8. Increase in the power of the solar tracker vs static panel

Figure 9, obtained from empirical data using the MPUNAB interface, shows the same behavior as Figure 7, obtained from PVSyst simulation. It is noteworthy that between the 12 and 13 hour, the power output of the solar tracker is almost the same as the fixed panel since, at that moment, both are completely horizontal. By comparing the empirical and theoretical response, it is observed that the solar panels, both the fixed and the tracker, have a maximum electrical power peak of 155 Watts. Some differences can also be observed in the curves of Figures 8 and 10, mainly caused by disturbances, which, in the case of PVSyst, are distributed uniformly over the day and not at specific moments, as is the real case.

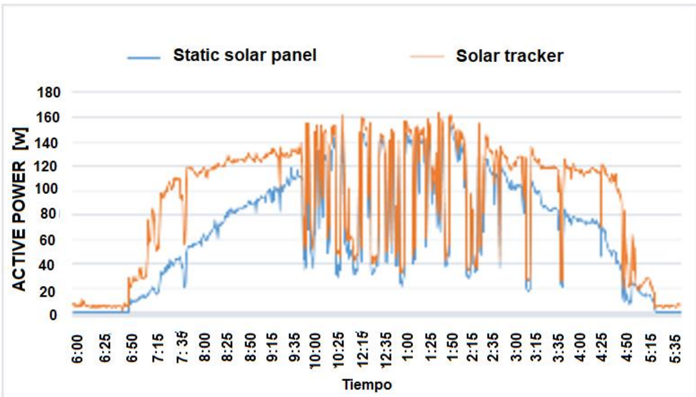

Figure 9. Power of the solar tracker vs power of the static panel

Some studies in countries that are part of the intertropical convergence zone are within a range of energy production icrtement between 11-46%, using solar trackers [23-26]. In turn, as shown in the study conducted by [27], a one axis tracking system on Europe can increase the energy output from 12 to 20% compared to a fixed system, this document also provides graphs with a very similar behavior to that shown in

Figure 8, where it is demonstrated that the tracking system generates more power and, therefore, delivers more energy than the fixed panel. Similarly, in [28] conducted the study of a solar tracking system of two levels which was compared with fixed systems, the study presents graphs showing the increase in efficiency and power delivered by the tracking system. Several studies on the increase of the energy production by tracking systems have been published in India. The study realized in [29] analyses data obtained from the comparison of a dual tracker system and a fixed system, measured hour by hour for a period of 9 hours; the study considers external factors such as rainfall and/or cloudiness present in the area on the day of the data collection. This study concludes that the solar tracker system can increase power output up to 46% in the morning and 25% in the afternoon if weather conditions are favorable.

Comparing the fixed panel and the tracker, it was established that the solar tracker of a single axis considerable more efficient than the fixed panel in Colombia, with values that exceed a 19% in the increase of the energy production for the worst case, and up to 48% in the better conditions. In terms of power, the average power output for the fixed and tracking panels is 80 and 120 Watts, respectively.

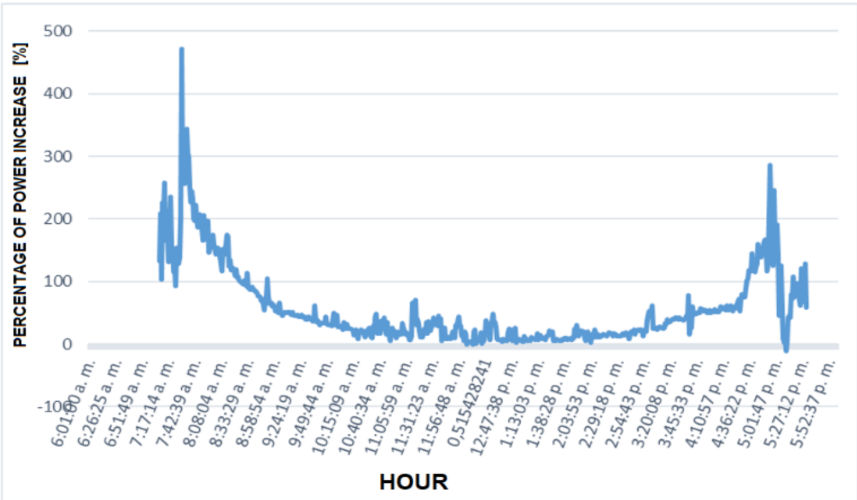

Figure 10. Increase in the power of the solar tracker vs static panel-experimental data

For future works, this type of analysis can be carried out for dual-axe trackers, single-axis tracker, and fixed system. Such analysis can expect results that show an increase of up to 25% in the energy output for the dual-axis tracker [30] compared to single-axis trackers. Moreover, future analyses should include economic factors that consider the cost of the technology and the increase in the energy production.

4. CONCLUSION

The design, testing and validation of a single-axis solar tracker has been presented together with the corresponding monitoring tool, developed in the LABVIEW interface. Likewise, a methodology to determine the location of the sun was formulated and applied, allowing the posterior developing of a control algorithm easy to implement in a digital processing system. Furthermore, the PD control has a reliable transient response, with no current peaks observed that can increase the power consumption and shorten the actuator life time. The use of the designed control system and the solar tracking produces an increase of 19% in the power output on days with heavy rain and clouds. In addition, this increase can reach up to 47.84% when weather conditions favor the capture of the maximum possible irradiation. With an average daily power increase of up to 47.84%, and an average 19.5% increase in the monthly energy production, the use of single-axis solar trackers proved an important potential for the photovoltaic energy in latitudes similar to those of Colombia, especially for large solar farms projects. It was validated experimentally, the behavior of the solar tracker in terms of increased energy production versus a simulated stationary panel through PVsyst, finding that the powers during the day measured by the interface MPUNAB have the same behavior, and in terms of increased energy production, there is only a difference of 0.5%, this reveals the reliability of the software model and the correct use it makes of the climatic variables of the place. The behavior pattern coincides with previous studies carried out for equatorial latitudes.

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