Article

Design PV Tracking System according to Efficiency in Function of Orientation

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Abstract: This article proposes a new photovoltaic (PV) solar tracker design based on the advantage that installation latitude offers according to efficiency in function of orientation (EFO) of PVs. First, is described a methodology to let incorporate a low-precision, low-cost and high-availability solar tracking mechanism and control system. The design methodology considers the installation location (latitude and azimuth) as a starting point for establishing an adequate angular range of EFO, simultaneity the aspects of available technology and the knowledge accords to developer. Finally, the design technique is experimentally validated by the implementation of a solar tracker at latitude of 28° longitude of 109° and evaluates the efficiency on a specific day. According to result the feasibility of this type of solar tracker for latitudes close to or greater than 30° is highlighted, given that this tracking system costs 30% less than traditional commercial systems as slew drive with its incorporation of lower-resolution azimuth tracking mechanisms. It also increases collection efficiency by 26%, just as continuous or time-based dual-axis solar trackers do, without the more complex controls and mechanisms of these designs.

Keywords: PV Solar Tracker, Design Methodology, Efficiency Function of Orientation

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1. Introduction

Photovoltaic (PV) systems frequently incorporate solar tracking systems to maintain their orientation so that the incident solar radiation is normal to the PV surface to increase collection efficiency [1, 2]. Multiple solar tracking systems have been developed, and they can be divided into two types: passive tracking systems, which present low resistance to wind action and feature low installation and maintenance costs, with collection efficiency increases up to 23% [3], and active tracking systems, which can be single-axis and have been reported to increase the collection efficiency by 12-25%, following the solar trajectory along one axis, which can be horizontal, vertical, polar and tilted [4,5]. Active dual-axis solar trackers have been reported to increase the collection efficiency from 30-45%. In general, these dual-axis sun tracking systems can either rotate about the polar and solar declination axes or the azimuth and elevation axes [5]. To achieve this design, ring-rail-type structures, which are designed to support very large PV systems subjected to strong winds [6], can be used mounted on pedestal or central support structures that incorporate linear actuators for polar tracking and a slew drive for azimuth tracking [7,8].

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In addition, prototypes of other dual-axis solar tracker variants have been presented. For example, [9,10] introduces solar trackers that incorporate robotic actuators, and [11] presents a solar tracker that incorporates complex four-bar mechanisms for solar tracking. To improve the accuracy and performance of dual-axis solar trackers, electronic monitoring systems for obtaining Maximum Power Point Tracking (MPPT) in tandem with solar tracking [12] have been incorporated. Other approaches incorporate different control variants, such as tracking algorithms and techniques with sensors, astronomical equations, diffuse logic, neural networks, time-based tracking systems and Petri networks, according to the recent state-of-the-art review presented in [13,14]. Other studies propose the incorporation of low-cost control devices, such as those presented in [15,16,17], among others.

In addition to the control methods previously mentioned, which propose strategies and establish performance evaluation mechanisms for single-axis solar tracking, and the definition of three points spaced according to the sun's trajectory, either daily or annually, as demonstrated in [18,19 and 20], there are also time-based tracking methods, which essentially establish a forward motion of the azimuth tracking at a rate of 15 per hour during a previously established period of the day [21], according to conditions at the installation site. Finally, hybrid solar tracking systems have been proposed, which simultaneously incorporate time tracking and astronomical path equations, along with sensors for improving the robustness of the tracking control systems, as reported in the photovoltaic tracking state-of-the-art review presented recently by Nsengiyumva et al. [13].

However, according to the previously mentioned studies, no methodology has been presented so far for the development of solar trackers that exploit the advantage offered by the degree of latitude of the installation site for incorporating low-accuracy, low-cost control mechanisms and systems, which also maintain the PV within an adequate range of efficiency as a function of orientation (EFO) [22]. Accordingly, in the present work, a methodology based on the EFO of the installation site is presented, and by incorporating tracking points during the day with a daily tilt adjustment, this method facilitates the development of a low-cost solar tracker by incorporating low-cost, low-resolution control mechanisms and systems based on the available technology

2. Materials and Methods

2.1 Methodology description

The proposed methodology has the goals of developing a strategy for the design of a low-precision, high-efficiency PV tracking system and of facilitating the instrumentation and control required for the prototype. This methodology is based on the Norton design methodology [23]; through relevant modifications, it directs the developer during the design process, incorporating the prototype instrumentation and product control requirements according to the knowledge and devices available to the integrator. After applying this methodology, in addition to obtaining a functional and innovative prototype solar tracker prototype and documentation is obtained by proceeding through the sequential steps presented in Figure 1.

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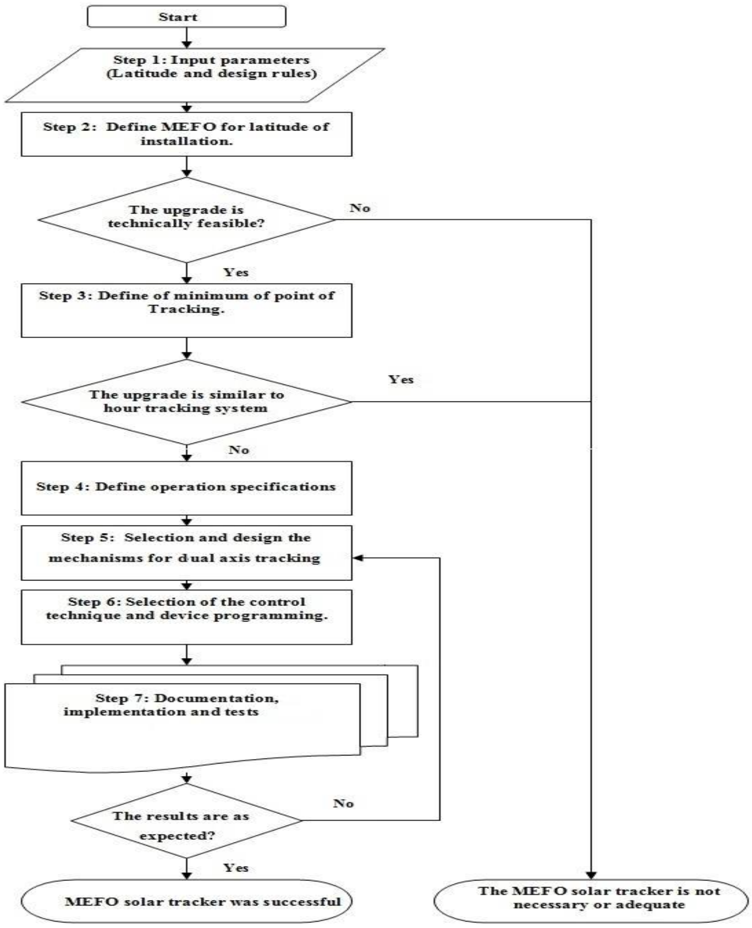

Figure 1. EFO solar tracker methodology.

Step 1.- Input parameters: This step defines the parameters and design rules for a new solar tracker, including latitude of installation established according to a global positioning system (GPS) or maps, available technology and the equipment resources. This information is obtained from manufacturers, suppliers, commercial equipment sellers, and developers.

Step 2.- EFO for installation latitude: Accord conceptual operational framework is necessary to establish the EFO based on the latitude of PV installation. For example, in [22], the EFO for a location (Bergen, Sweden) corresponds to latitude of 36°. The 100% efficiency for range of tilt angles are between 28° to 48° and orientation angles between -20° to 20°. Next, it is necessary to evaluate whether it is possible to design a new solar tracker with a low-precision PV tracking system with high efficiency, or decline and pursue another method of design, as described in [13].

Step 3.- Points and trajectory for solar tracking: This section establishes a minimum number of tracking points that can be managed by day according to the EFO range established in the previous step and verified the azimuth and elevation angles range based on the solar trajectory in the installation site throughout the year. According flow diagram of Figure 1 if the solar tracker has a large number of tracking points spaced 15 per hour in a continuous interval, we recommend using a time-based tracking method, as defined in [13].

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Step 4.- Operation specifications: The results of this step are the paragraphs and/or picture that describe the prototype solar tracker operation, detailing the events and actions occurring over time and including the labels of possible sensors and actuators needed for the instrumentation and control of the new solar tracker.

Step 5.- Selection and design mechanisms for dual axis tracking: This step consists primarily of the selection of mechanism in accordance with the capacities required for the solar tracker prototype, using comparison matrices that facilitate the selection of devices according to the evaluation criterion, where "H" is assigned to high values, "M" to medium values, and "L" to low values. In addition, calculations are performed on the structures and mechanisms required for develops the prototype, which are supported by computer aided design (CAD) tools and finite element analysis (FEA) and arithmetic calculations.

Step 6.- Selection of the control technique and device programming: The control technique is selected in accordance with the process to be performed (Grafcet, Petri Nets, Neural Networks, Diffuse Logic), considering the detailed description of the solar tracker prototype operation (Step 4) and the control device selected (FPGA, PLC, microcontroller, industrial PC) based on the previously selected technique. Finally, the program is developed according to the algorithm and control technique previously established in Steps 4 and 5.

Step 7.- Documentation, implementation and tests: In this step, the documents required for the instrumentation, control and construction of the prototype are recollect. These are typically electrical, pneumatic or hydraulic diagrams, component and prototype construction plans, instrument specifications and program source code. Once the plans and diagrams of the new solar tracker prototype have been developed, the construction and tests are performed to determine if the upgrade fulfils the expectations for the EFO solar tracker prototype. If the results are inadequate, it is necessary to return to Step 5 to consider necessary modifications until the results of the process of obtaining the new solar tracker prototype are satisfied.

2.2. Case Application

Step 1.- Input Parameters: The EFO solar tracker prototype will be installed at a site located at 28° latitude and 109° longitude. In addition, it must meet the following design criteria: low cost, low maintenance, high collection efficiency and improved performance against wind action. The specific parameter values are shown in Table 1.

Table 1: Solar tracker design parameters.

DESIGN PARAMETERS	VALUE
Latitude	**28**
Efficiency	**95% - 100%**
Maximum wind speed	**80 km/hr**
Capacity	**1 kW**
Cost	**Lowest Available**

Step 2.- EFO for installation latitude: Considering the design rules established in the previous step and the EFO according to the conceptual framework for PV system performance and presented in [22], it is possible to manage tracking errors in the azimuthal axis in a range of ± 30 and tracking errors for the tilt axis in a range of ± 28, maintaining a collection efficiency from 95-100%, as shown in Figure 2.

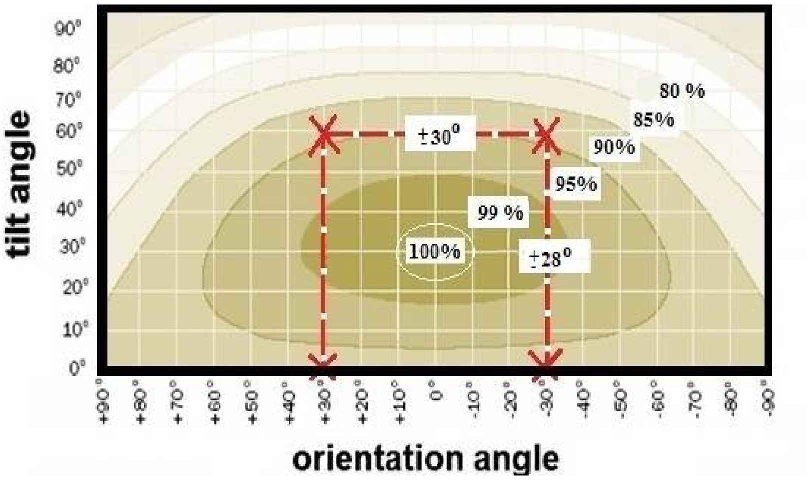

Figure 2. Angle range for a PV at 28° latitude with EFO of 95-100%.

Step 3.- Points and trajectory for solar tracking: Considering an advance of the sun of 15° per hour and accord to azimuth EFO have a range of ± 30° of defacement and hourly solar tracking of following from 6:00 a.m. to 6:00 p.m. the tracking can be divided into 3 spaced points and location according to table 2, with respect to the adjustment of solar height, it is proposed that the follow-up by means of adjust daily according to the declination considering that its greater than 16° and can managed ± 28° according a solar chart for a latitude of 28 ° North and this mechanism is a low cost.

Table 2. Azimuth Schedule of tracking

Position	Schedule of tracking (hours)	Azimuth (°)
P1	18:01 a 10:00	30
P2	10:01 a 14:00	90
P1	14:01 a 18:00	120

Step 4.- Operation specifications: These solar tracking systems follow the sun's trajectory using a three-point motion for azimuth tracking with a clockwise open-loop control system that operates from 6:00 to 18:00 over a day according to Figure 3 and use a linear actuator for tracking the declination over the year.

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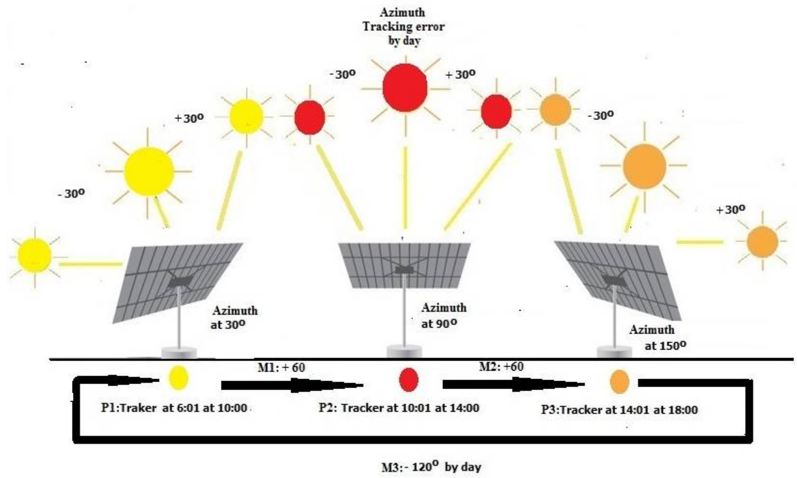

Figure 3. General Operation descriptions for the solar tracker prototype.

Step 5.- Selection and design mechanisms for dual axis tracking: The first component to design for the solar tracker is the PV system support structure, which in this case corresponds to a photovoltaic system of 1 kWe composed of four panels of 0.95 m x 1.05 m and 250 W. This supporting structure is designed based on computer-aided design software and finite element analysis CAD/CAE, in which different structures are proposed. An analysis of which structure presents better resistance against wind action is performed, using a wind speed of 120 km/hr, which is chosen based on the maximum wind speed records at the installation location [32]. According to the FEA analysis, the most appropriate structure uses structural steel (PTR-14, PTR-20) and ½" tubing, as shown in Figure 4.

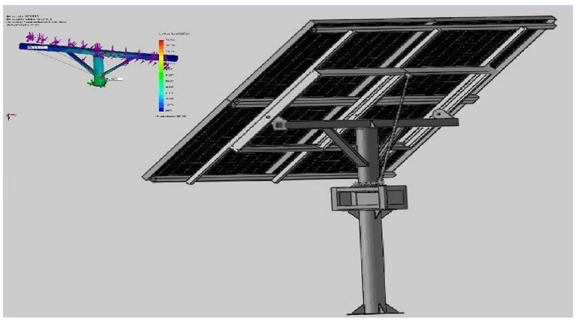

Figure 4. Proposed structure for solar tracker.

Next, the tracking mechanism is selected based on the decision matrix in Table 3. The most viable option is a DC gear-motor adapted to a transmission due to its low cost and high availability.

Table 3. Actuator selection for mechanism tracking.

Mechanism	*Cost*	*Availability*	*Maintenance*
Gear-motor transmission and Lineal actuator	L	H	M
Two Slew Drive	M	M	L
Two Motor indexed	H	L	H

Next, the transmission is designed (Figure 5), which must achieve the proposed resolution without affecting the previously proposed structure. A bevel gear transmission with a total gear ratio of 8:1, composed of a gear-motor coupling dart (1), an upper panel support (2), and bevel gears for transverse coupling (3 and 4), is proposed. The transmission uses A36 steel due to its mechanical resistance.

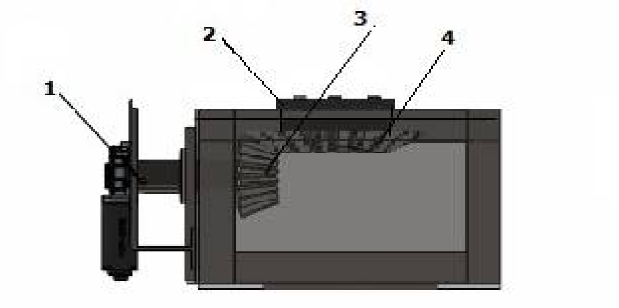

Figure 5. Proposed azimuth solar tracker mechanism.

According to the calculations for a gearmotor and linear actuator (such as the example shown in Figure 6, which is a worm-rack type system with a torque of 80 N/m coupled to a transmission with a step ratio of 12, 0.2 m in diameter), it is possible to withstand the torsion moments caused by wind action over the PV system area.

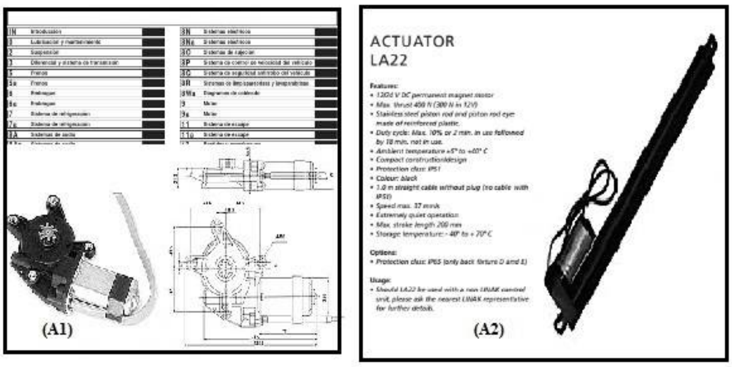

Figure 6. Selected actuators.

Step 6.- Selection control technique and device programming: According to the data previously obtained to fulfil the design requirements, minimizing the amount of movement and taking advantage of the ± 30 windows for maximum efficiency, a time tracking system is proposed. This follows the sun's trajectory using three points separated by 60 in the azimuth axis (Figure 5), using a microcontroller with limited digital I/O and the capacity to perform basic arithmetic operations and manage the date and time. The tracking begins at point P1, located at 30 above the azimuth axis; the tracker remains at this point until 10:00. Then, one minute later and by activation with an actuator A1, it will move to point P2, located 60 from the previous point, where it will stay until 14:00. Once again, one minute later and by the activation of actuator A1, it will move to point P3 located at 60 from the previous point, where it will remain until 18:00. Finally, one minute later, it will return to point P1 by the action of actuator A1 to turn 120 in the opposite direction. It is desirable to incorporate a manual alignment system for the installation of the solar tracker (Figure 7).

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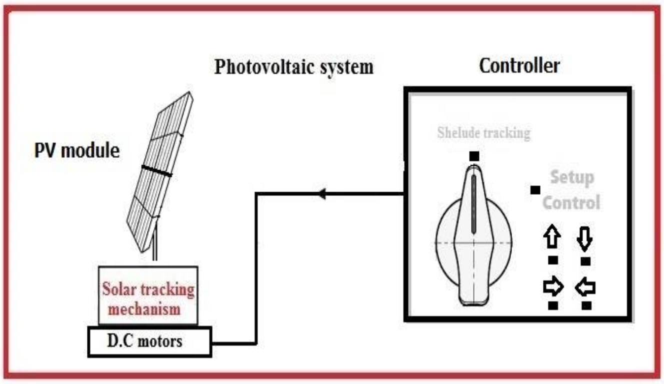

Figure 7. Proposed solar tracking open loop control.

A device to perform the proposed control of the A1 activation controller (DC gear-motor) must be selected. A controller with the capacity to manage dates and hours and perform some arithmetic operations is required. We considered a programmable logic controller, a microcontroller and an industrial PC, which are compared in Table 4, which also shows the comparative criteria.

Table 4, Control device selection matrix.

Device	Cost	Availability	Maintenance
PLC	M	H	H
Microcontroller with H bridge	L	H	H
Industrial PC with output interfaces	H	L	L

The most viable option for the development of the control system is a system based on a microcontroller combined with an H bridge due to its low cost and its capacity to perform basic arithmetic operations and facilitate the incorporation of a manual alignment system for the installation of the solar tracker, according to the schematic shown in Figure 8.

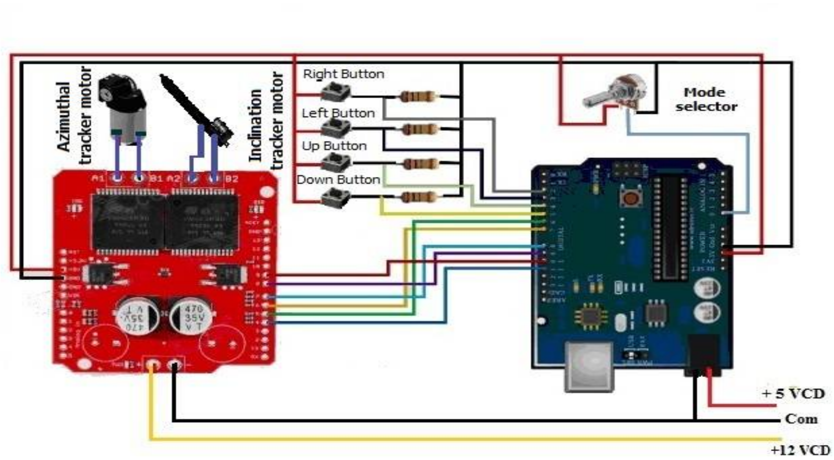

Figure 8. Controller connections schematic.

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In table 5 before developing the controller, a control technique must be selected according to the characteristics and the operation of the solar tracker prototype mentioned in the previous step.

Table 5. Selection of the control algorithm technique.

Technique to elaborate the control mechanism	Hardware requirements	Complexity	Knowledge
Grafset	M	M	H
Petri nets	H	H	L
Flow Diagrams	L	L	M

The Grafcet technique is selected, mainly because the authors have a large amount of knowledge in applying this technique. Figure 9 illustrates the Grafcet technique used to develop the program for the low-cost microcontroller selected in the previous step.

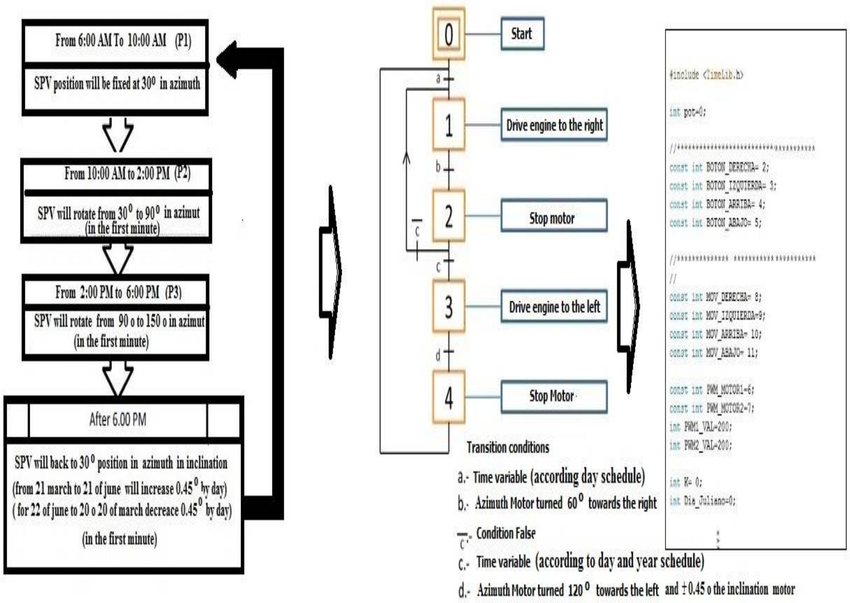

Figure 9. Controller programming process.

Step 7.- Documentation, implementation and tests

a) Documentation

To proceed with the development of the solar tracker prototype, it is necessary to generate documentation as; the specification of the actuators (Figure 6), the microcontroller electronic circuit diagram (Figure 8), the source code of the solar tracker control program (Figure 9), and the structural plans of the tracking system (Figure 10).

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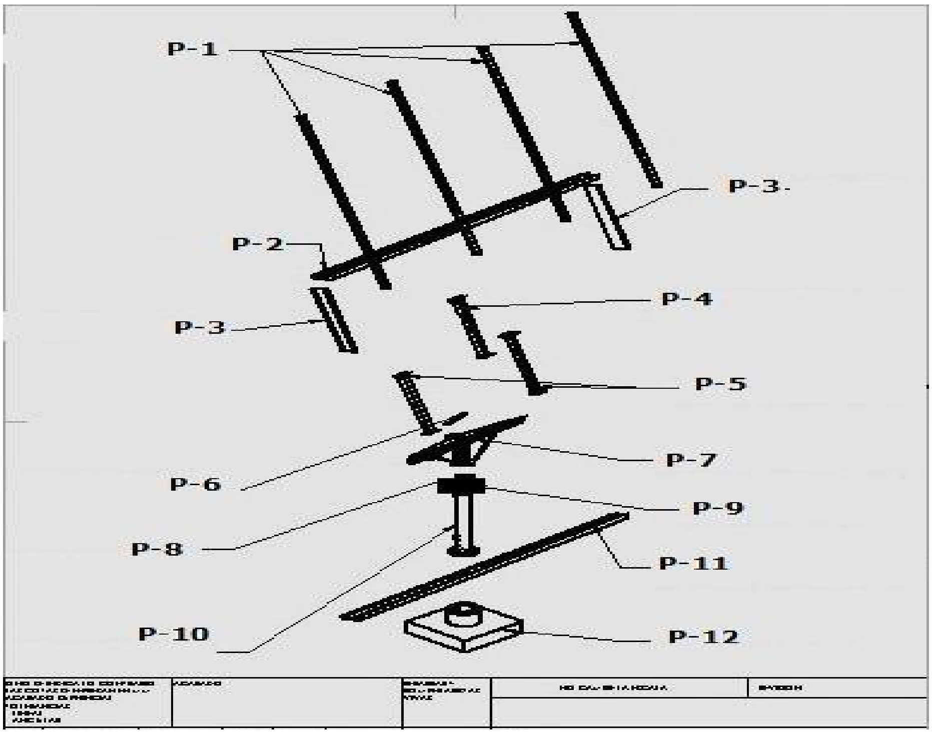

Figure 10. Plans for the proposed structure.

b) Implementation

The final implementation of the EFO solar tracker prototype is shown in Figure 11, which shows the location of the control system and the A1, A2 actuators. The actuator A1 and mechanism according to [24] have a 30% low cost than a slew drive uses for solar tracker [25].

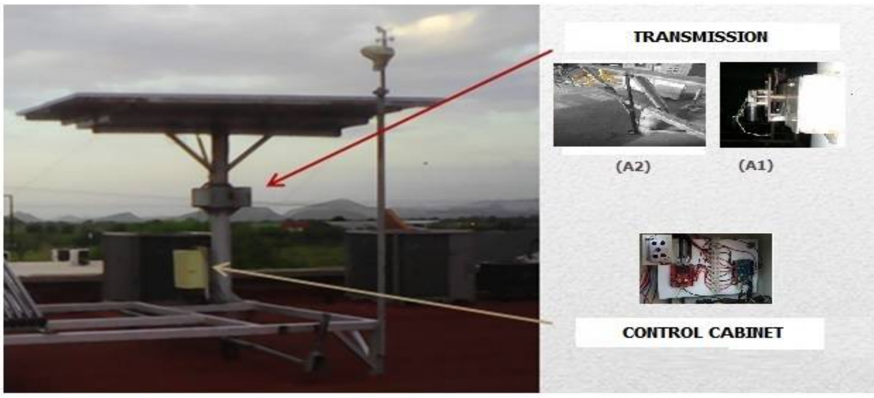

Figure 11. Solar tracker prototype and components.

c) Test

The solar tracker prototype's resistance to wind was tested for a specific place (28° latitude and 109° longitude) during 2017. During this period, the tracker remained operational and withstood maximum wind gusts of 84 km/h according to data obtained from the weather station installed at the same location. The solar tracker efficiency was maintained within a range of 26-30%, as shown by the results of the experimental test performed on May 4, 2018. The details regarding instrumentation and recording of the PV efficiency measurements are provided in the result section.

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3. Results

The efficiency measurement was performed by recording the power delivered by the fixed PV module and by another tracking PV module model ERDM 225, The measuring voltage and current was performed using the electric circuit shown in the schematic of Figure 12.

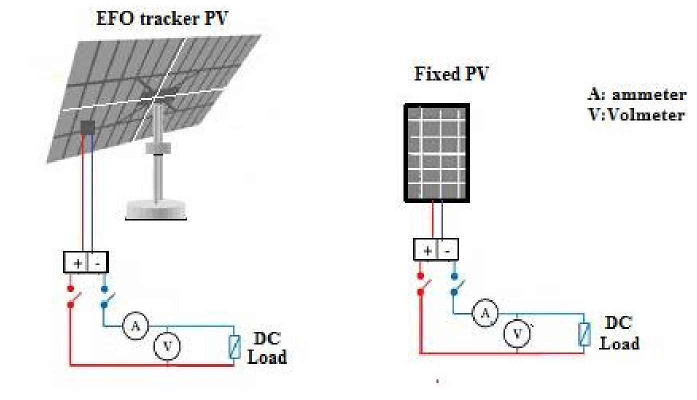

Figure 12. Schematic of the PV power measurement.

The comparative results for the PV panel placed in a solar tracker prototype located at Cd. Obregon, Mexico (28° latitude and 109° longitude) on 04 May 2018 are shown in Figure 13. Data were captured every 30 min for the average daily production achieved by the panels performing the tracking. The tracking solar panel collected 26-35% more energy than the energy collected by the fixed photovoltaic panel.

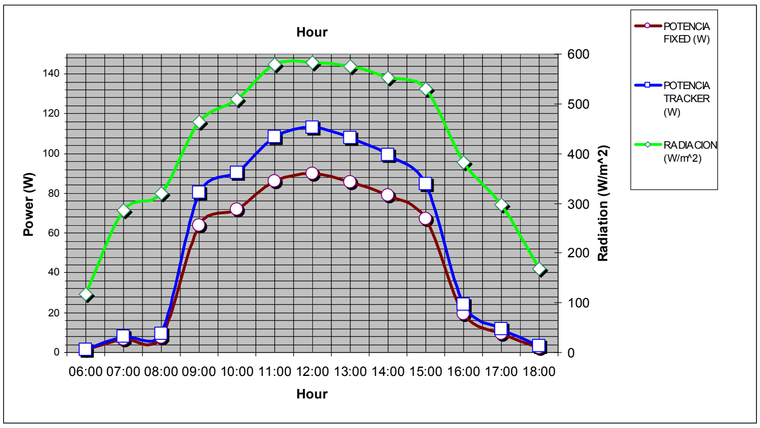

Figure 13. Energy produced by the photovoltaic panels (fixed and tracking).

4. Conclusions

The photovoltaic solar tracker design is based in a methodology that is recommended to use in a latitudes in close proximity to 30 because the increase in collection efficiency of the solar trackers as similar to others solar trackers that incorporate better control tracking technology and more precise mechanisms but with more costly and complex and evaluating the possibility of adjusting the EFO to incorporate this type of tracker at other latitudes by means the proposes methodology.

The proposed methodology let to develops a low cost photovoltaic solar trackers and the case of latitudes close to or greater than 30° is highlighted, given that this tracking system (azimuth mechanism) costs 30% less as than traditional commercial systems by means incorporation of lower-resolution azimuth tracking mechanisms. It also increases collection efficiency by 26%, just as continuous or time-based dual-axis solar trackers do.

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Conflicts of Interest: The authors declare no conflict of interest.

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