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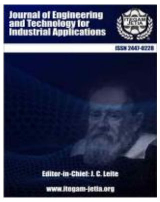

RESEARCH ARTICLE OPEN ACCESS

DESIGN OF THE POSITION CONTROL SYSTEM OF PARABOLIC SOLAR CONCENTRATORS THROUGH COLLECTOR BY ELECTRICAL DRIVE

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ABSTRACT

Solar energy is one of the most important renewable energies due to its abundance and sustainability. This has led to a great development in the technologies used to obtain them, which are increasingly effective and varied, such as solar thermal collection technology. Solar thermal collection technology to obtain a greater capture of solar energy requires a monitoring mechanism for its use, either manual or automatic. This work provides a proposal for automatic solar tracking in Parabolic Trough Solar Concentrators, with the aim that they absorb as much solar energy as possible during the day from the position control of their reflectors to faithfully follow the solar path. The positioning of these collectors is done by an electric drive and using a Raspberry Pi single-board computer as a control and command unit. The geared motor and the other elements that conform to the system were selected in compliance with the requirements of the application. The programming of the position control system implemented in the Raspberry Pi is carried out and the collectors are provided with wind safety. Finally, the results of the simulation tests made with the help of the MATLAB tool are carried out and shown. In addition to an economic and environmental analysis that demonstrates the reliability of the project. The system design generated a satisfactory result for sun tracking using the developed algorithm.

I. INTRODUCTION

Solar energy is one of the cleanest energy resources, it does not modify the environment and above all it is free. This energy is obtained from the Sun and, depending on the solar radiation incident on the Earth, it can be harnessed by its heating capacity (solar thermal energy) or directly by the photoelectric effect (solar photovoltaic energy). Moreover, it is considered the backbone of any sustainable development program [1],[2] and from this point of view, it offers several advantages. The use of this energy resource allows the recovery of degraded lands, the increase of regional and national energy independence, as well as the diversification and security of energy supply, and the improvement of the quality of water resources.

Nowadays, energy consumption has become a basic factor for many aspects of human activity and progress [3]. Therefore, energy is indispensable for the advancement of a country, so much so that the rate of energy consumption is closely related to the degree of economic development. On the other hand, the various global developments such as global warming, pollution, scarcity of non-renewable resources, and high energy demand also constitute a reason why renewable energies are in great demand [4]. The use of the solar resource produces no polluting emissions to the environment and is obtained from a virtually inexhaustible natural source [5].

Solar energy currently holds incredible promise as renewable energy to meet the world's energy demand [6]. The solar energy absorbed by the Earth in one year is approximately 20 times the energy stored in all the fossil fuel reserves in the world [3]. According to the 21st World Energy Council Study [7], by the year 2100, 70% of the energy consumed will be of solar origin. Likewise, the use of technologies for obtaining solar energy presents great potential in tropical countries where the intensity of solar radiation has a high value, between 900 [W/m]^2 and 1000 [W/m]^2 when it is incident perpendicularly on a surface. This represents an average of approximately 400 [W/m]^2 on the earth's surface [8], and more than 5 kWh per day per square meter as an annual average value.

II. THEORETICAL REFERENCE

II.1 PARABOLIC SOLAR CONCENTRATOR THROUGH COLLECTOR

Solar thermal energy has now achieved a degree of maturity, both economically and technically, and is thus a good option for the production of electrical energy. Parabolic solar concentrators through collectors (PTC) are part of this solar energy strategy [2]. These have several application alternatives among which are to satisfy the heat requirements of processes in the chemical and food industry, in processes such as drying, sterilization, and cleaning, as well as the conditioning of industrial buildings [9]. This energy alternative avoids the use of conventional energy sources and therefore reduces the environmental impact produced by the use of the latter.

There are several types of solar thermal collectors that, although they have the same principle, have different characteristics:

- Stationary" collectors: These types of collectors are stationary all day long and operate with global solar energy [10]. They are located at an angle capable of covering the declination of the Sun from the summer solstice to the winter solstice [11]. Evacuated tube and flat plate collectors are within this classification.

- Tracker" collectors: These are collectors that need a solar tracking system to move according to the path of the Sun throughout the day [10]. Within this group can be found the collectors with concentration [11]. As the absorption area of these collectors is small, these systems must be perpendicular to the sun to reach higher temperatures.

- Low temperature (30ºC - 100ºC): This range is achieved with flat plate collectors.

- Medium temperature (100ºC - 400ºC): These are achieved with linear or spherical concentrators, and include parabolic solar concentrators through collectors.

- High temperature (400ºC-3000ºC): These are achieved with point concentrators [10] such as Dish Stirling and central tower fields.

Solar concentrators through collectors are included in solar thermal technologies. This technology takes advantage of the sun's radiation and uses mirrors to reflect it onto a focal line, through which the thermal energy of the solar radiation is transferred, to obtain a high temperature and generate steam [12],[13] move a turbine, and produce electricity.

The operation of the PTC is based on solar tracking and the concentration of solar rays on high thermal efficiency receiver tubes located in the focal line of the cylinders. A working fluid circulates through these tubes, either water or some kind of thermal oil [11], which can reach a temperature of 400°C. Therefore, they are included in the medium temperature solar collectors [10],[14]. This system takes advantage of the property of parabolas [15]: any ray hitting the parabola will be reflected in the direction of a point called the focus.

The PTC concentrates sunlight 30 to 60 times the normal intensity on the absorber, heating the heat transfer fluid to high temperatures [16]. These collectors centralize about 99.95% of the direct solar radiation (DNI) [17], typically generating 100 kW/m^2.

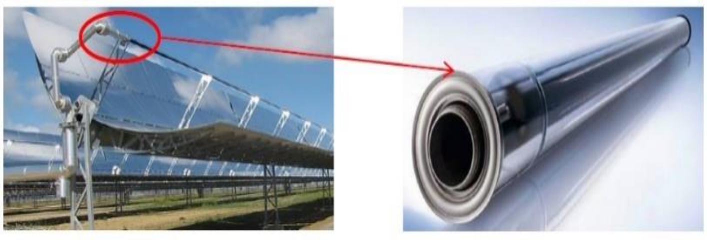


Figure 1: Parabolic solar concentrator trough collector and absorber tube.
Source: Authors, (2023).

The parabolic-cylinder solar concentrator through collector system takes full advantage of direct solar radiation if there is an automated solar tracking mechanism that follows the sun's path throughout the day [18]. The solar tracking system consists of a device that rotates the parabolic-cylinder reflectors of the collector around a tracking axis.

To increase the amount of solar energy reaching the receiver [19], it is necessary to include a solar tracking system that can follow the trajectory of the sun during the day and as a consequence, vary the position of the PTC. The tracking system must have the ability to return the collector to its starting position to wait for the Sun at sunrise, after having tracked the trajectory of the Sun throughout the day. In addition, it must follow the sun regardless of the weather, as long as there are no strong gusts of wind that could damage the collectors and their parts, so the tracking system must also include a safety system to protect against these cases and bring the collectors to a safe position.

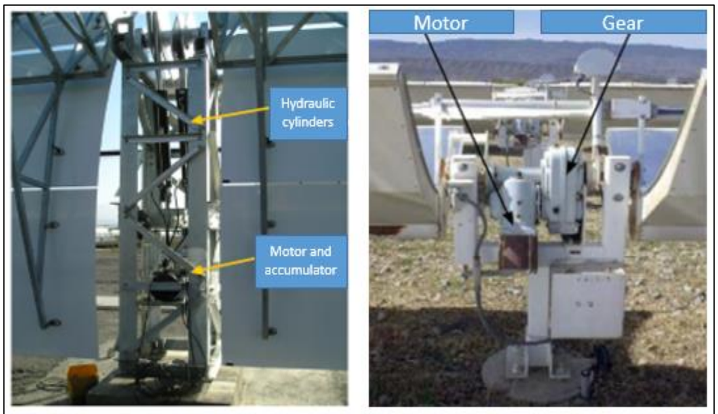


Figure 2: Basic elements of a PTC.
Source: Taken from [20].

II.2 SOLAR TRACKING ALGORITHMS

Solar tracking can be performed using different types of algorithms:

- Sensor tracking: They use photoresistive sensors, which vary the resistive value depending on the amount of light they capture [21]. With this difference, the position of the motor is controlled. It presents difficulties in the presence of cloudy weather.

- Tracking by sundial: The structure moves at a constant speed, it is independent of the weather but does not take into account the nonlinearity of the solar trajectory.

- Tracking by calculated coordinates: It tracks the trajectory of the Sun between each position by calculating its astronomical coordinates. They are immune to cloudy days or any other circumstance that may produce errors in tracking.

Different control strategies can be found:

- Closed loop: tracking systems using this variant are based on feedback transferred from sensors [22] capable of providing information about the solar position concerning the earth plane.

- Open loop: this type of control bases its operation on the estimation of its inputs using only the current state and a computer algorithm to determine whether its inputs have achieved the desired objective [23]. This control lacks feedback in the system because there is no sensor to provide information for correcting the solar tracking.

Trackers according to the type of motion:

- Dual-axis trackers: these trackers have two degrees of freedom acting as axes of rotation, which are typically normal to each other. The primary axis is the one that is fixed concerning the ground and the secondary axis is referenced to the primary axis [24]. This tracking system can change the altitude and azimuthal degrees of the solar collection system, thus tracking the Sun in East to West and North to South directions to maximize energy production [25], making full tracking of the Sun. Although the performance of the installation may be superior compared to single-axis trackers [26], they have a higher cost.

Figure 3: Two-axis solar tracker.

Source: Taken from [11].

- Single-axis trackers: these are the simplest trackers, generally use less energy and are less complex than dual-axis trackers energy and have a lower complexity compared to dual-axis trackers [6]. They have only one degree of freedom so the rotation of the pickup surface is done on a single axis. The limitation of this type of tracker is that it cannot perform a full tracking of the Sun since it can only complete tracking of the Sun since it can only follow [26], for example, the azimuth or the solar inclination, but it can only solar inclination.

PTC is mainly used with a single-axis tracking scheme, as this is mechanically simpler and involves lower costs and lower thermal losses as there is no passive piping [10]. Generally, the collectors can be oriented in two ways: East-West, such that it follows the Sun from North to South , or , in North-South orientation [27] where the collector follows the Sun from East to West.

Tracking on an East-West oriented axis requires less adjustment. However, despite having the aperture always facing the Sun at noon this solar tracking system presents a much lower performance during the morning and afternoon, due to the increase in the angle of incidence. PTCs with an East-West orientation [28] collect more solar energy during winter periods.

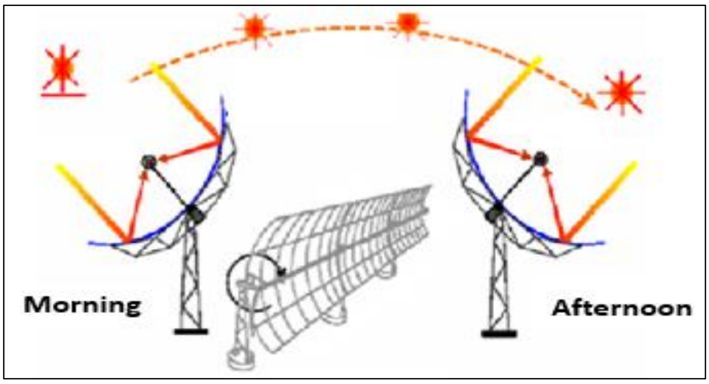


Figure 4: Solar tracking system with one axis of motion.
Source: taken from [22].

III. MATERIALS AND METHODS

III.1 STRUCTURE OF THE TRACKING SYSTEM

Based on the above analysis, the tracking system for this application was designed and developed. This system will be constituted by a single axis of movement, following the trajectory of the Sun in the sky from North to South. In other words, following its height, and therefore the collectors will be oriented East-West. Astronomical scheduling is chosen as the tracking method, so it will be necessary to have accurate time and day data.

The collectors are positioned by electric drive and controlled by a Raspberry Pi microcomputer. An anemometer and a wind vane will also be needed to ensure the safe operation of the collectors when functioning during strong gusts of wind.

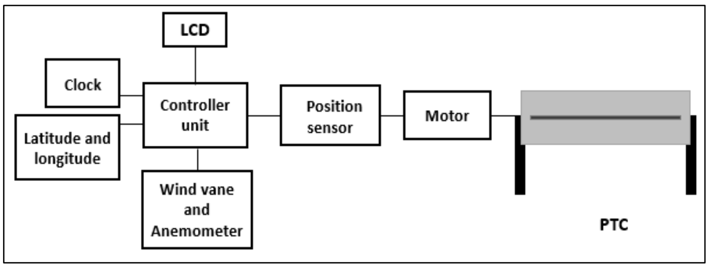


Figure 5: Architecture of the proposed monitoring system.
Source: Authors, (2023).

The basic elements that make up the system are: the motor, controller unit, Raspberry Pi, clock, anemometer position sensor, weather vane and a Liquid Cristal Display (LCD).

III.1.1 Requirements of the Collector Position Control System

The proposed tracking system is controlled by a programming algorithm that, based on astronomical calculations, determines the position of the Sun throughout the day, from which the tracking is performed. This system is composed of a positioning system, and a control unit with its respective accessories and elements for the measurement of the variables necessary for such control.

It is desired to control the position of two parabolic solar concentrators through collector of 12 m long and 2.5 m in diameter. To move these collectors it is necessary that the positioning system can develop a moment of 800 Nm.

III.1.2 The Positioning System, Electric Drive

The positioning system consists of a geared motor coupled to the axis of the PTC to carry out its movement to follow the solar trajectory. This movement will be executed according to the orders received from the controller board of the system.

For the selection of the elements that compose the system, the following factors must be taken into account:

The movement of the Sun across the sky is very slow so the tracking systems are characterized by developing small velocities. Considering normal motor speeds if directly coupled, such a slow speed of motion would not be achieved with adequate torque to drive solar tracking [29]. Therefore, a gear drive system is necessary to reduce the motor speed.

Generally, solar tracking uses a transmission system with a gear ratio between 10,000: 1 and 30,000: 1; thus, the rotational motion of the solar tracker is usually faster than the rotational motion speed of the Sun. This is why on/off type solar tracking control systems are used to synchronize the angular rotational motion of the solar tracker on the ground with the apparent motion of the sun in the sky.

III.2 CONTROL ELEMENTS

III.2.1 Control Unit: Raspberry Pi

The Raspberry Pi is characterized by the possibility of running several Linux distributions and other operating systems such as RISC OS and can be used in electronic projects. In addition, it is capable of doing many of the features offered by a desktop PC, such as running spreadsheet programs [30]. It is possible to connect USB peripherals such as a keyboard, mouse, webcams, Wi-Fi adapters, Bluetooth and many others.

For the implementation of the control algorithm for the solar tracking of this project, the Raspberry Pi 1 Model B+ board is chosen. This Raspberry Pi model has forty pins distributed in two columns of twenty pins each that constitute the general purpose input and output (GPIO) ports of the board, which can be seen in Figure 6.

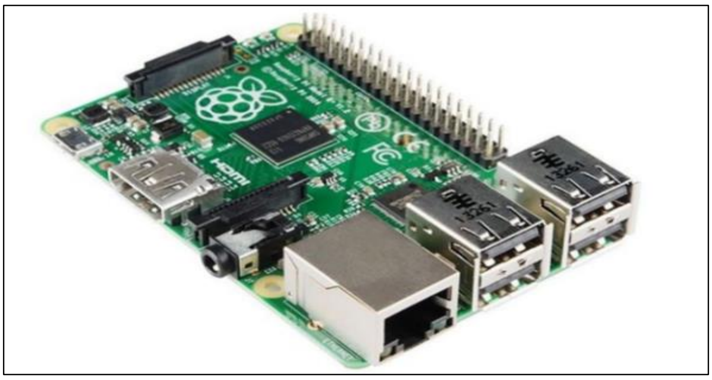


Figure 6: Raspberry Pi 1 Model B+ rev 1.2.
Source: Taken from [31].

The system software is located in the micro SD memory inserted in the Raspberry Pi and the programming language used for the implementation of the control algorithm is Python. Using the Anaconda tool, Spyder is used as an integrated development environment (IDE), dedicated to scientific programming in the Python language, a free and simple developmental environment.

III.2.2 Real-Time Clock

A real-time clock (RTC) is responsible for keeping the time and date updated. It consists of an oscillator crystal that generates a frequency of 32768 Hz and a chip capable of keeping the internal registers [31] in which it stores the date and time data updated.

As the Raspberry Pi is designed to be a very low-cost computer there are many of the features provided by traditional computers have been omitted as is the case of the RTCs [32].

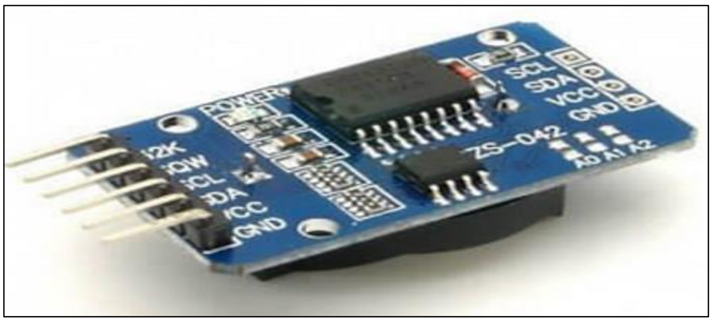


Figure 7: RTC to Raspberry Pi.
Source: Taken from [33].

III.2.3 Absolute Encoder

The actual position of the PTC needs to be known and compared with the tracking angle that it should have according to the programming calculations. For that, a device able to measure this variable and provide this data to the controller unit is needed to control the position of these collectors. An absolute encoder is the most suitable device to meet the objective of measuring the position.

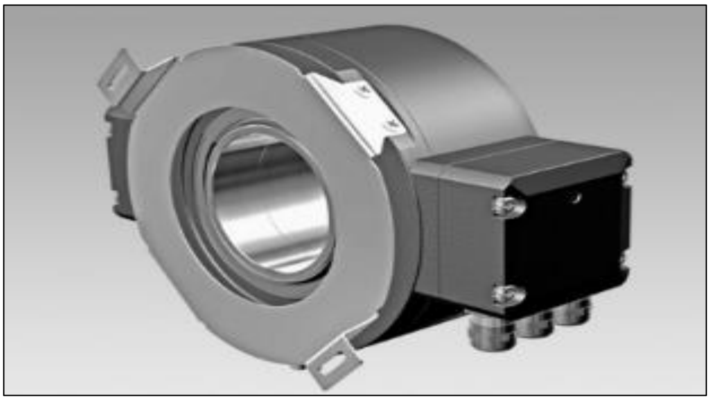


Figure 8: Absolute encoder.
Source: Taken from [34].

III.2.4 LCD

For displaying tracking angle data and the actual position of the collector, a 16-column, 2-row LCD can be selected. This allows 16 characters to be displayed in each row [35], with blue backlight feedback and white characters.

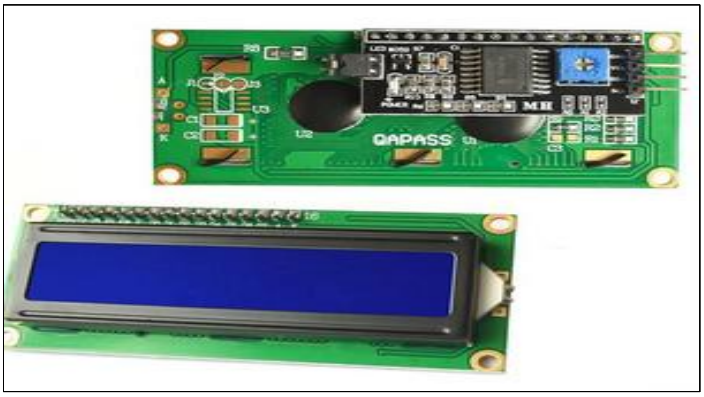


Figure 9: LCD.
Source: Taken from [35].

III.2.5 Voltage Level Converter

The GPIOs work with 3.3 V to be able to use the devices that work with 5 V. It is necessary to use a voltage converter to be able to use these devices with the Raspberry Pi. The voltage level converter selected for this project consists of a printed circuit board with 4 bidirectional converter lines, composed of 4 FETs, with 10 KΩ resistors. It works up to 1.8 V on the low side and up to 10 V on the high side.

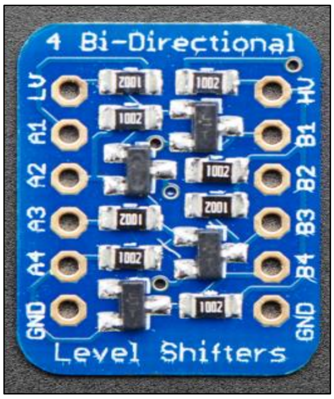


Figure 10: Bidirectional voltage converter.
Source: Taken from [36].

III.2.6 Optocoupler

An Optocoupler is used to work with 3.3 V input and 24 V output compatible with the proposed Raspberry.

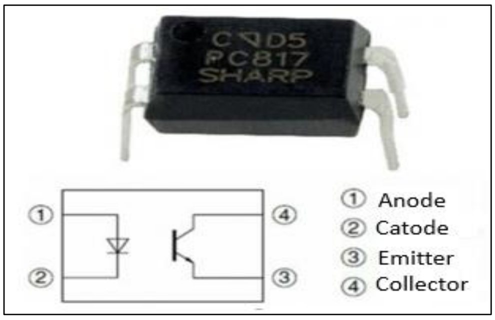


Figure 11: Optocoupler.
Source: Taken from [37].

III.2.7 Battery

The battery should be used as a backup in case of failure of the system power supply. It is advisable to use a lithium polymer battery because they provide longer battery life and allow higher loads [38]. Lithium polymer batteries are composed of solid polymers, which replace the flammable liquid electrolytes used in other types of batteries [28], thus increasing safety when used for any type of application.

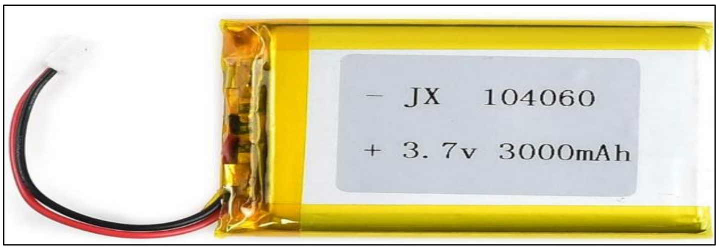


Figure 12: Lithium polymer battery.
Source: Taken from [38].

III.2.8 Safe Position of the Collectors in the Wind

The presence of strong winds causes damage to the components of the collector and its structure.

The PTC can operate as long as the wind speed does not exceed 14 m/s (50.4 km/h) [39], however, when it exceeds 5 m/s (18 km/h) the collector performance will start to be affected. In the case of winds between 14 and 40 m/s (144 km/h), the collector must be brought to a safe position, which varies according to its structural design.

The safe position generally coincides with the rest position to which the collector will be taken at the end of the day to spend the night in this position and be ready for the sunrise, shortening the start-up times. This position will also be used during days when the tracking system is down for maintenance or other factors. The safe position of the collectors is set below the horizontal, thus facilitating maintenance tasks and preventing the first rays of the day from concentrating on the absorber tube when it is not in operation.

III.2.9 Measurement of Wind Speed and Direction

The wind is a natural, generally horizontal movement of air masses [40]. Thermal imbalances between unlike places produce differences in atmospheric pressure, which cause winds. The wind speed can be measured using an anemometer, and the wind direction is measured by a wind vane, which gives the direction from which the wind is coming.

III.2.10 Anemometer

The analog anemometer sends a voltage that varies linearly with the speed of rotation of the blades. As the Raspberry Pi does not have analog input/output pins, it is necessary to use the digital signal generated by the anemometer. The selected sensor must be designed to work outdoors [41] and requires a voltage of 7-24 V to work properly.

Figure 13: Anemometer.
Source: Taken from [41].

III.2.11 Wind Vane

To determine the wind direction, it is necessary use a wind vane. By using a rotary encoder the sensor can indicate which cardinal point coincides with the direction from which the wind is coming.

Figure: 14 Wind vane.
Source: Taken from [42].

III.2.12 Collector Safety System

If the PTC is tracking the Sun normally and the wind speed exceeds the set limits, it must be moved to a safe position. One option is to take the maximum speed at 40 km/h and the position 90° below the horizontal, the same position that is set for the rest and maintenance state of these collectors.

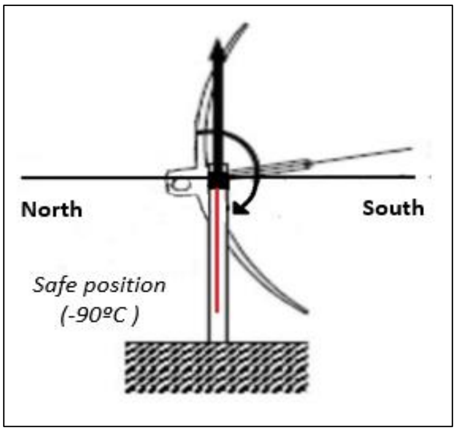


Figure 15: Safety and rest position.
Source: Authors, (2023).

III.2.13 Control System

The tracking control is performed from the positioning algorithm programmed in the Raspberry Pi, based on astronomical calculations to determine the position of the Sun. The time and date for the calculations are provided by the real-time clock. These calculations determine the reference point of the control system and based on the measurement of the actual position of the PTC provided by the position sensor, the tracking error is determined and if it exists the Raspberry Pi, sends a command signal to the geared motor to adjust the position of the collectors with the desired position in the programming. The system also receives information about the wind speed, acting as a safety system.

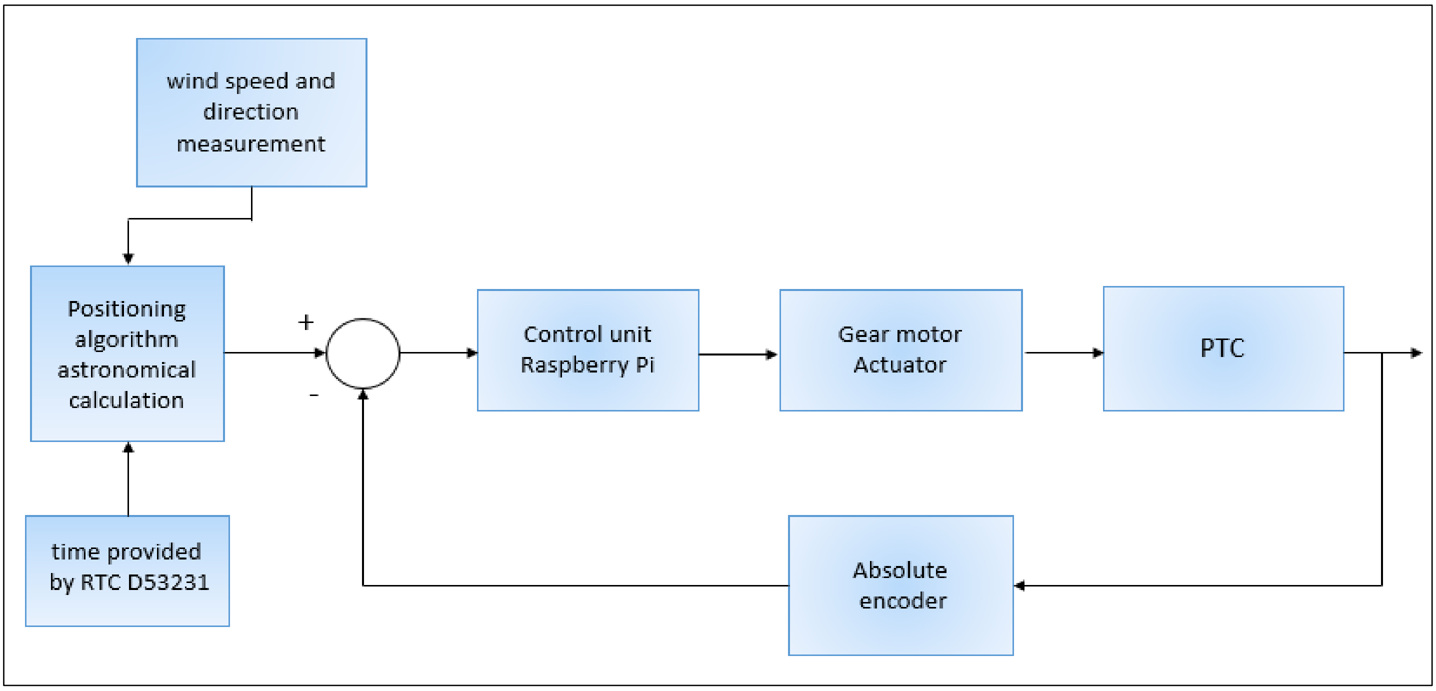


Figure 16: Position control system.
Source: Authors, (2023).

III.2.14 Command Signal and Control Algorithm

The solar tracking control driven by the slewing actuator only requires incremental corrections in the angle of the tracking system to achieve effective solar tracking [28].

The motor will only move when a position error is detected. The resolution of the tracking system is adjusted, for PTC, 0.5° is adequate according to the diameter of the absorber tube.

As a control philosophy, it is also used the obligation that at the end of the day, the PTC must be at rest position and ten minutes before the next day's sunrise it will go to the zero position, being available to start tracking. In the case of detecting wind speeds higher than the allowed limit, the monitoring is stopped by bringing the collector to the safety position, leaving it only when the wind speed returns to the limits established for the protection of the PTC during a determined period.

IV. RESULTS AND DISCUSSIONS

The validation of the control algorithm is performed using the MATLAB tool, a high-performance technical computing environment [43] that integrates numerical analysis, matrix computation, signal processing, and graphics. Figure 17 shows the flowchart describing the process of the implemented solar tracking algorithm, from which the tests are performed.

In this environment, the performance of the system based on astronomical calculations, implemented in the Raspberry Pi, was evaluated for the determination of solar angles and other variables such as solar time, solar azimuth, solar height, sunrise, and sunset for different days of the year. Figure 17 shows the flowchart describing the process of the implemented solar tracking algorithm, from which the tests are performed.

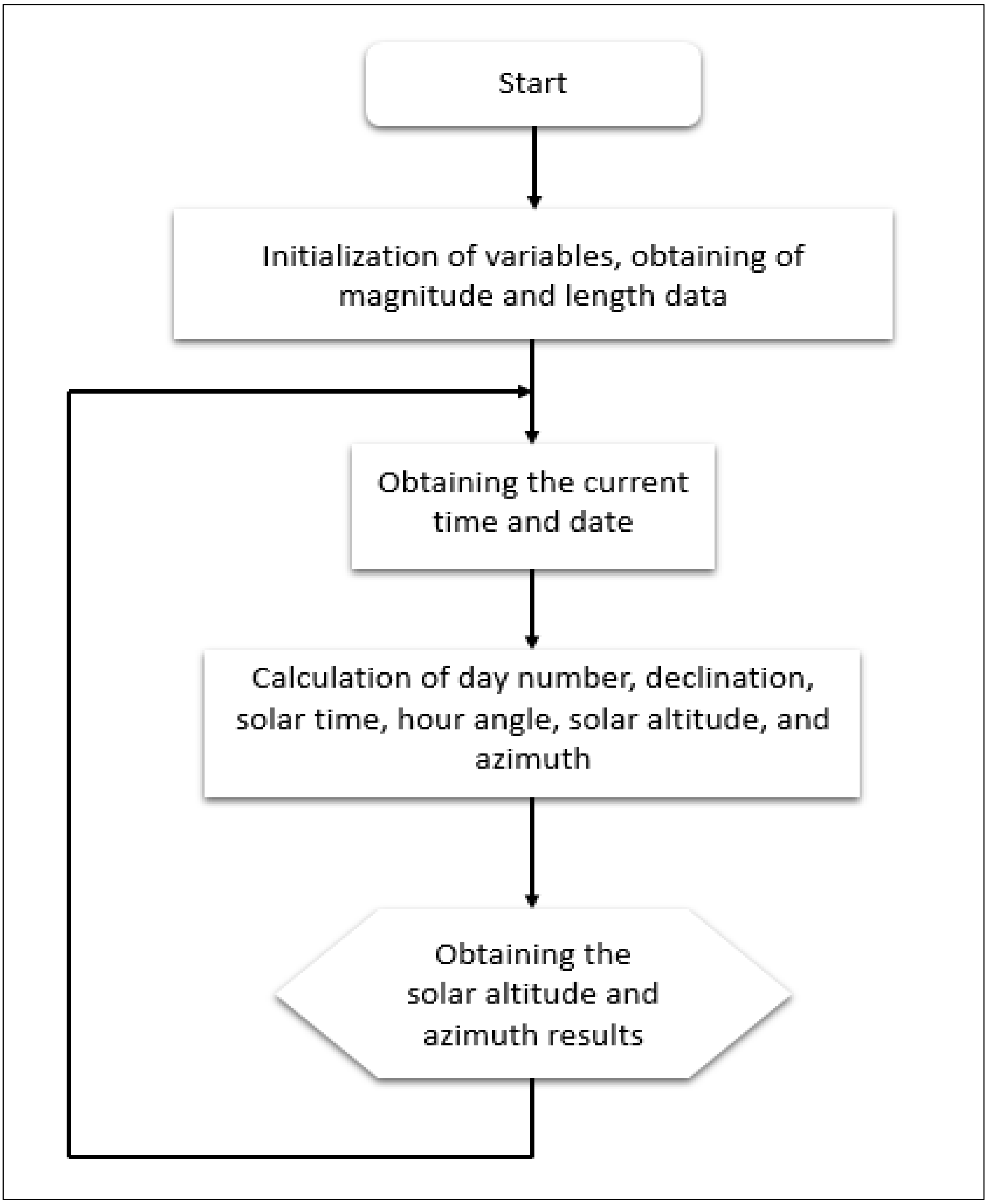


Figure 17: Block diagram of the designed algorithm.
Source: Authors, (2023).

As a result of the execution of this algorithm, Figures 18 and 19 show the behavior of the azimuthal angle and the solar elevation angle obtained by the system according to the latitude and longitude data of the city of Santa Clara, belonging to the province of Villa Clara, Cuba on September 22, 2021, day in which the autumnal equinox takes place, between the time of Sunrise (7:12:55 AM) and Sunset (7:10:56 PM).

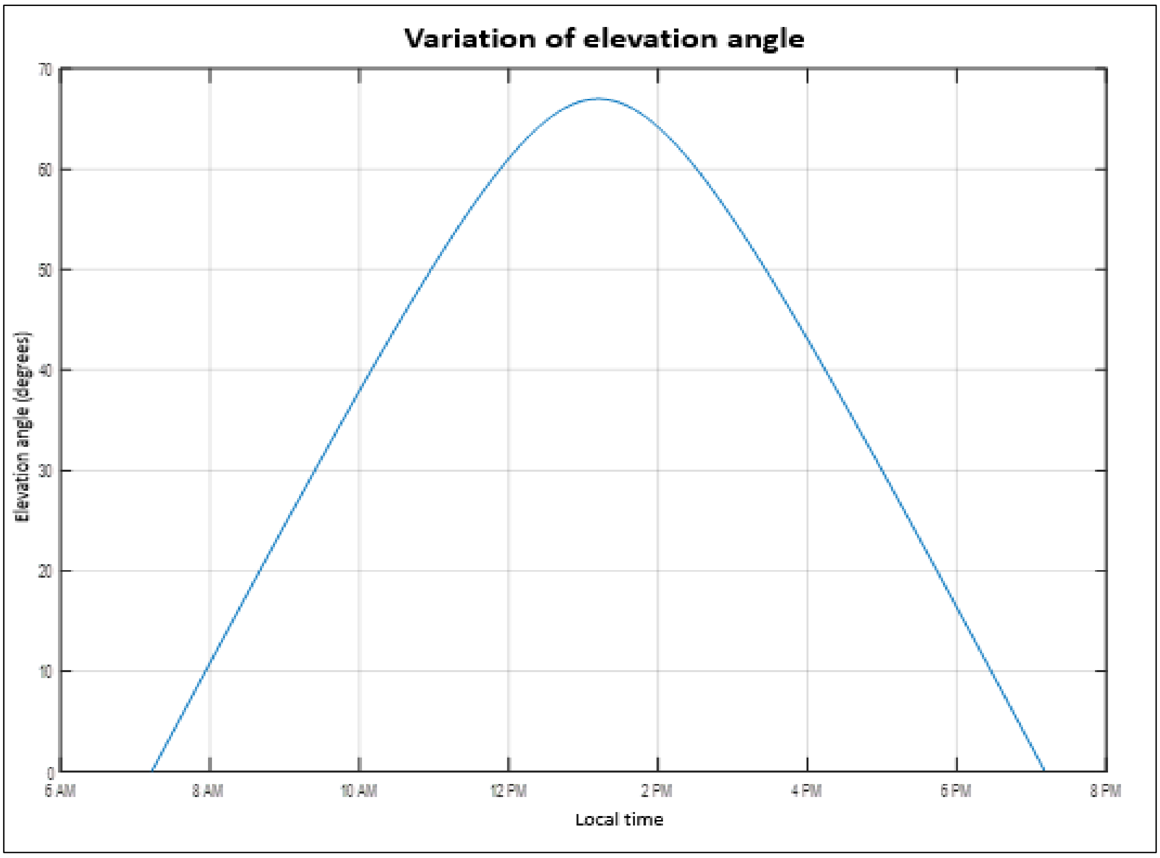


Figure 18: Behavior of the solar elevation angle.
Source: Authors, (2023).

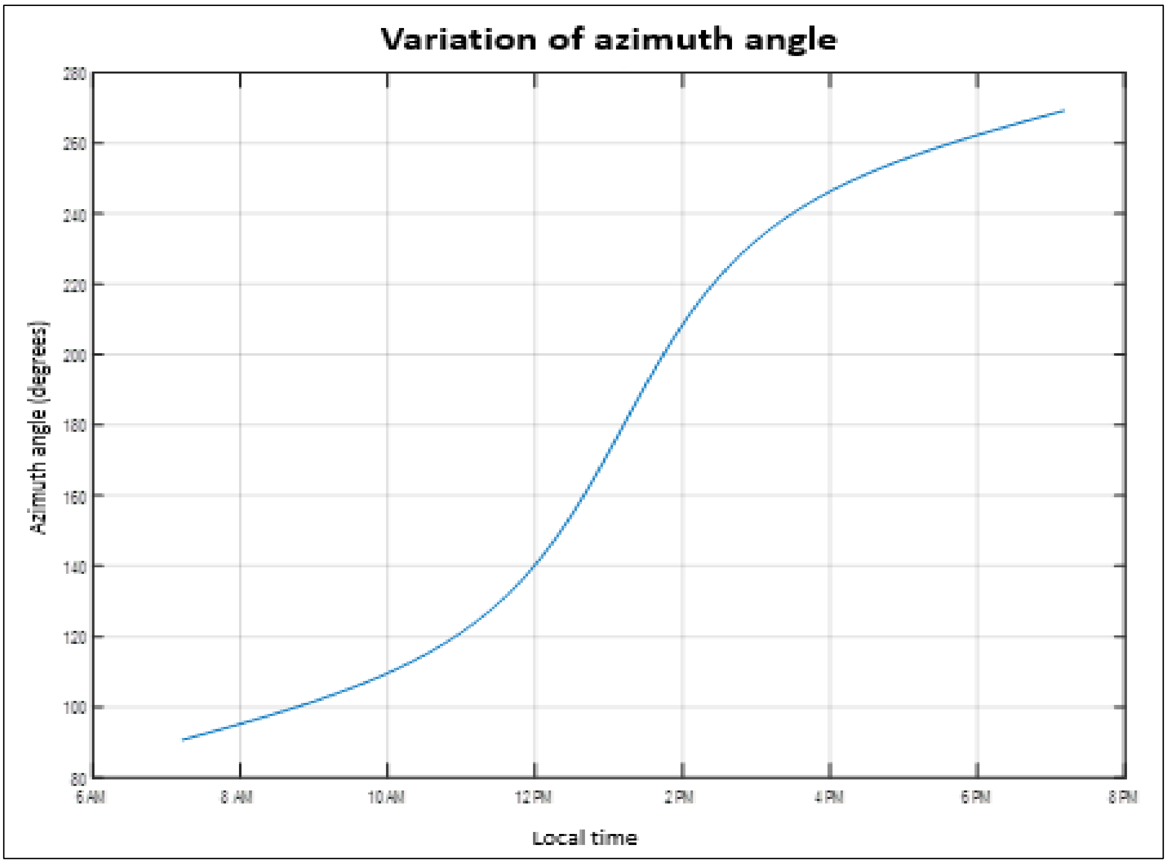


Figure 19: Behavior of the solar azimuth angle.
Source: Authors, (2023).

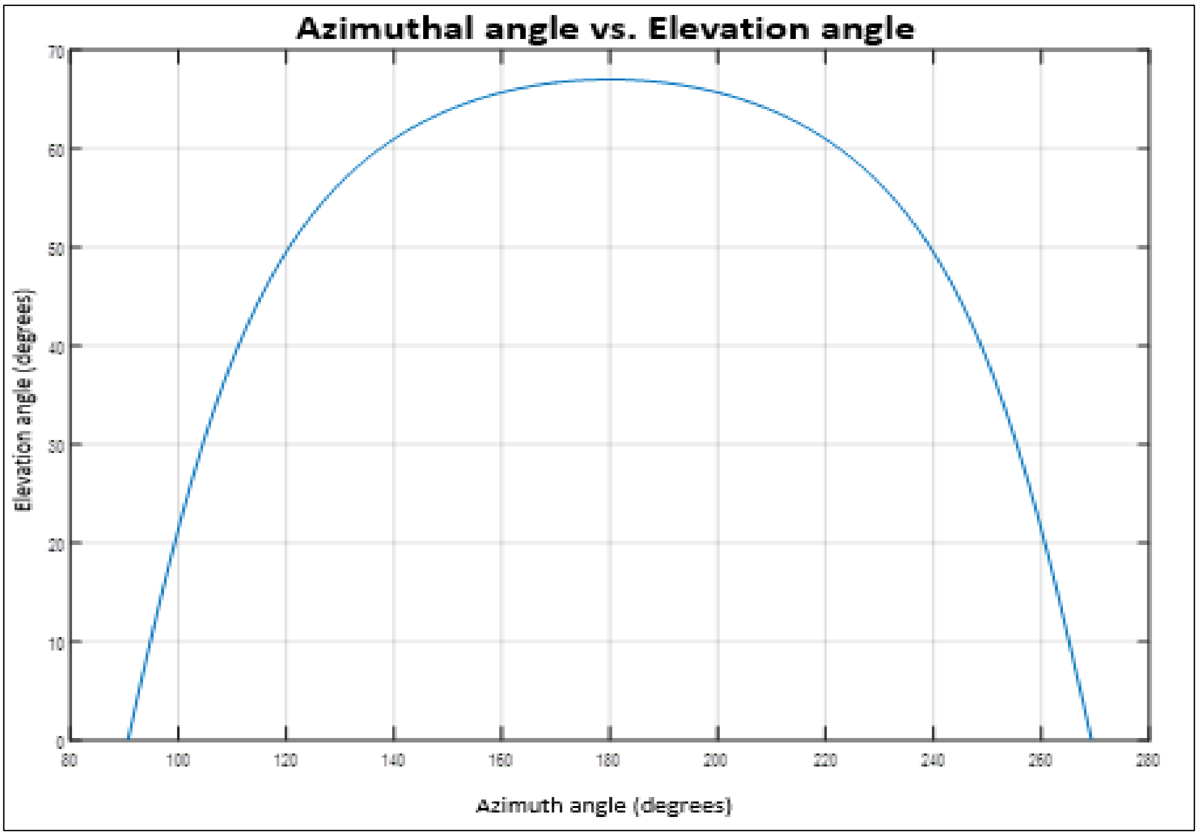
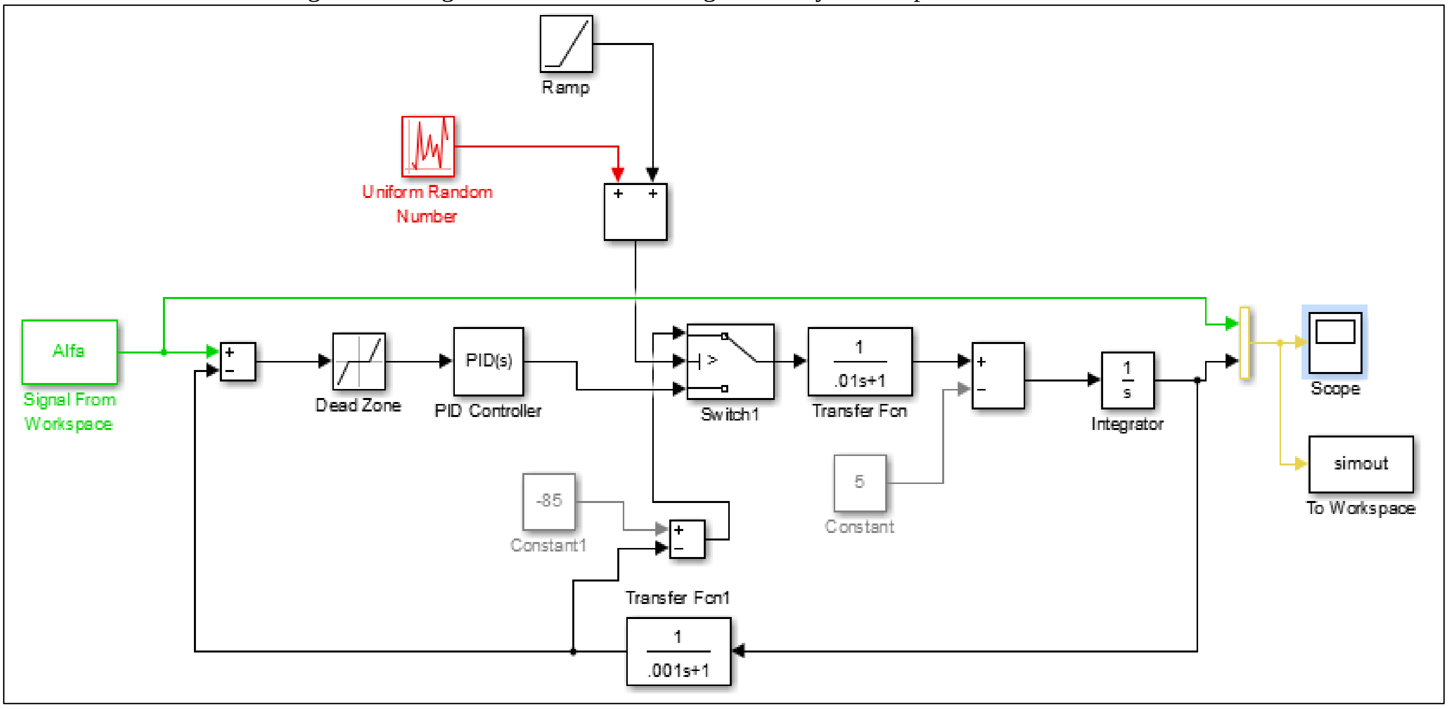


Figure 20: Behavior of the solar azimuth angle together with the solar elevation angle.
Source: Authors, (2023).

For these tests, an equinox day was chosen since it is the time of the year when day and night have the same duration.

Knowing the effectiveness of the tracking algorithm through astronomical programming using MATLAB Simulink, the behavior of the control system to follow the calculated ideal position and its response in the presence of strong gusts of wind is evaluated. Figure 21 shows the diagram used to evaluate the behavior of the system with the designed controller when it is perceived that the velocity of the wind exceeds the limit established for the application.

Figure 21: Diagram of the solar tracking control system implemented in Simulink.



Source: Authors, (2023).

As shown in the previous figure, the control system also has a Proportional Integral Derivative (PID) controller to ensure the correct behavior of the tracking system in a steady state. Figure 22 shows the behavior of the system with the controller to a change in the reference input unitary step type.

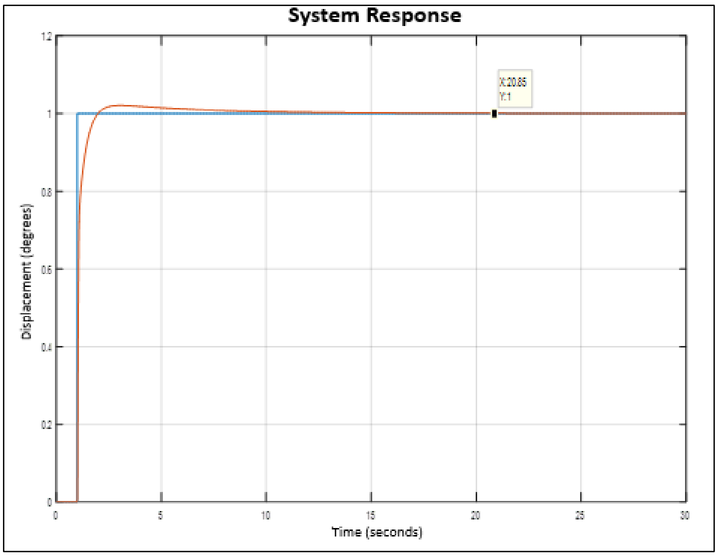


Figure 22: Response of the system with the designed PID.
Source: Authors, (2023).

As can be seen, the controller stabilizes at approximately 20.85 seconds and with a maximum overshoot practically null.

When the wind speed exceeds the limit value determined by the programming, the collectors are directed to a safe position below the horizontal. Figure 23 shows the behavior of the system under wind disturbance.

V. CONCLUSIONS

The designed position control algorithm for the Parabolic Solar Concentrators Through Collectors guarantees the correct tracking of the sun and the safety of the collectors under strong wind gusts. In addition, the correct selection of the hardware and software elements that compose the system allows the proper connection, integration, and operation of the system, designed according to the system requirements. The designed PID controller guarantees a fast response and ensures a correct steady-state operation. The position control using the astronomical programming method for calculating the solar position yielded excellent results.

VI. AUTHOR´S CONTRIBUTIONS

Conceptualization: José Abreu García, Ariel Barreiros Albo and Lianet Consuegra Morales.
Methodology: José Abreu García, Ariel Barreiros Albo and Lianet Consuegra Morales.
Investigation: José Abreu García, Ariel Barreiros Albo and Lianet Consuegra Morales.
Discussion of results: José Abreu García, Ariel Barreiros Albo and Lianet Consuegra Morales.
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