Solar tracking systems in compound parabolic concentrators

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Abstract. The utilization of solar energy as a sustainable and clean alternative to fossil fuels is gaining importance in today's world. Solar concentrators, particularly compound parabolic concentrators (CPCs), are effective devices for harnessing solar energy. Solar tracking systems are used in conjunction with CPCs to optimize energy output by aligning the concentrator with the sun's movement throughout the day and year. This article explores the use of solar tracking systems in compound parabolic concentrators, highlighting their advantages, limitations, and ongoing research efforts for performance enhancement.

In this study, a north-facing solar water heater system with a CPC design was developed, utilizing renewable solar energy. The system consisted of a high-reflectance aluminum foil concentrator, insulated with polyurethane foam and covered with a commercial aluminum casing. The receiver was composed of a copper tube coated with matte black absorptive paint. The control system was implemented using a Programmable Logic Controller (PLC) and tested against an Arduino Mega board. The PLC was chosen for its superior performance and stability. A PLC algorithm was developed to enable solar energy tracking, and climatic data was obtained using a Davis weather station.

The data from the meteorological station at the Polytechnic University of Puebla provided a one-year history, including over 200 sunny days in 2021. The data demonstrated the effective utilization of solar radiation in the region, with temperatures reaching or exceeding 100 °C for approximately 7 to 8 hours when the solar tracking system was employed.

The control system incorporated two 150 Wp 12 VDC solar panels to power a DC motor. The control algorithm was programmed using MATLAB software, providing response graphs for the motor. The power, angular velocity, and torque equations were used to determine control parameters for frequency conversion and selection of protective devices. The commonly used PID (Proportional, Integral, and Derivative) control and the proposed Fractional Order PID (FOPID) control were investigated.

The integration of FOPID control into digital devices required the use of the Z-transform. The Z-transform definition for sampled functions was presented. Block programming using Simulink software was employed, as it allows programming in both continuous and discrete domains. The block diagram for the FOPID control system programmed in Simulink using Freescale technology was provided.
The validation of the control system was performed using a PLC implementation of the FOPID control, and the results demonstrated its effectiveness. The system achieved stable temperature responses, with minor variations due to thermal inertia.
In conclusion, this technological project implemented at the Technological University of Puebla demonstrates the potential of solar energy utilization, specifically with compound parabolic concentrators and solar tracking systems. The findings contribute to the conservation of the environment and highlight the importance of sustainable energy sources.

Keywords: Solar tracking systems, compound parabolic concentrators, control.

1 Introduction

The use of solar energy as an alternative to fossil fuels is becoming increasingly important due to the need for sustainable and clean energy sources. One of the most effective ways to harness solar energy is using solar concentrators, which focus sunlight onto a small area, thereby increasing the intensity of the radiation and allowing for more efficient conversion into electricity or heat.

Among the different types of solar concentrators, parabolic concentrators have proven to be particularly efficient, especially when used in conjunction with solar tracking systems. By following the relative movement of the sun in the celestial vault throughout the day and the year, solar tracking systems ensure that the concentrated sunlight is always directed towards the receiver, maximizing energy output.

However, traditional parabolic concentrators have limitations in terms of the range of angles at which they can effectively concentrate sunlight. This has led to the development of compound parabolic concentrators, which have a wider acceptance angle and can therefore be used with solar tracking systems to achieve even higher efficiencies.

In this article, we will explore the use of solar tracking systems in compound parabolic concentrators, highlighting their advantages and limitations, as well as current research efforts aimed at improving their performance.

2 State of art

One of the population’s main energy demands is related to heat process and hot water for sanitary purposes. To meet this demand in a sustainable way, solar energy is a very attractive alternative.

In this way, Compound Parabolic Concentrators (CPCs) are some of the most promising technologies in solar energy systems, due CPC is considering very close to be ideal solar concentrator [1,2], CPC systems are designed for medium temperature solar applications (100 - 250 °C) [2-5], they can offer a superior yearly energy delivery when comparing to conventional stationary water heating devices (i.e. traditional flat solar collector [2,6]

Taking advantage of this last energy feature, CPCs can be built with lightweight and inexpensive materials [2,6,7], coupled with their reduced size compared to parabolic collectors, reducing the initial investment cost, and facilitating the implementation of a low-cost solar tracking system.

Although the advantage of CPCs is that they usually require little or no adjustment in angular position (depending on orientation) and when savings are required, only seasonal adjustments can be made in the year [2,8].

M. Beschi carried out a robust design of a fractional order control applied to a solar furnace; his proposal has some considerations that simplify the calculation of the control law. Beschi's methodology allows the user to make the margin phase invariant over a range of the system response. Minimizing at the same time the maximum sensitivity [9]. In addition, due to the wide range of temperature values, a gain in the System is proposed as a solution to the programming problem, in order to obtain a uniform response in the behavior at different work points. Experimental tests, carried out in the solar furnace of the Plataforma Solar Almería, demonstrate the effectiveness of the proposed models both in monitoring the solar trajectory and in rejecting disturbances [10].

In Serrano-Aguilera's article, mathematical methods used in solar collectors are reported in order to carry out a more precise monitoring of the solar path.

Wanjun Qu reports very interesting work on trajectory tracking systems for solar collectors located in a solar collector field [11].

Sopasakis explains how a fractional order controller works in discrete time [12,13].

Finally, in the work of Divya Shah, a fractional order control is implemented in an FPGA using functions in the domain of the Z transform [14].

The MFOPID is the proportional integral and derivative control of fractional order of multiterms, that is, it is a control that includes not only an integral and derivative term, but also includes more than one integrator and more than one fractional order derivative but of different orders.

3 Materials & Methods

In the Fig. 1, a north-facing solar water heater for residential use is shown, designed to align with the global position angle of the installation location, utilizing renewable energy (solar). It consists of a concentrator with a high reflectance aluminum foil, insulated with polyurethane foam, and covered with a commercial aluminum casing. As for the receiver, it is composed of a copper tube coated with matte black absorptive paint. Regarding the control system, tests were conducted with both the PLC and Arduino Mega board to optimize energy utilization. The PLC was ultimately chosen due to issues encountered during the testing phase with the Arduino board (false contacts and disconnection).

An algorithm was developed for the electronic control system using a Programmable Logic Controller (PLC), which programmed the function for solar energy tracking. Additionally, a Davis weather station was employed to obtain climatic data.

Fig. 1. Solar CPC systems.

In this regard, the data produced by the meteorological station at the Polytechnic University of Puebla, with a one-year (2021) history, provides statistical data for over 200 sunny days (refer to Fig. 2).

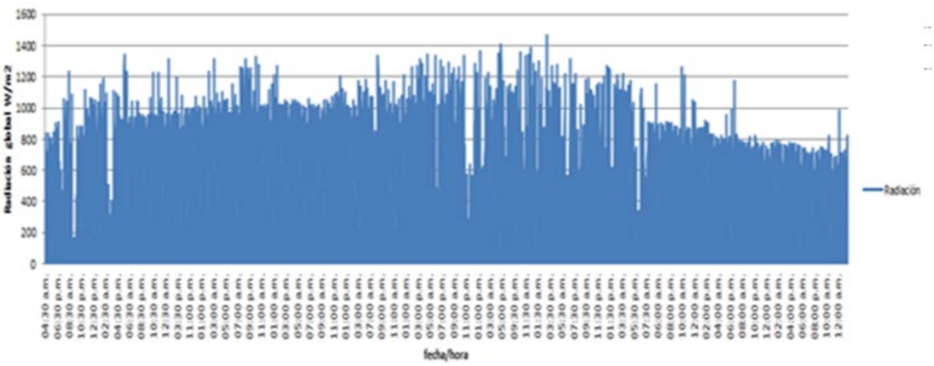

Fig. 2. Climatic data (solar radiation) Source: Puebla UP Weather Station.

This indicates the utilization of solar radiation in this area of Puebla. Moreover, temperatures equal to or greater than 100 °C can be consistently achieved in intervals of 7 to 8 hours when the solar tracking system is employed.

It is important to note that the system is equipped with 2 150 Wp 12 VDC solar panels, which power a DC motor. For the control of the DC motor, a code was developed using MATLAB software to obtain response graphs for the motor. These parameters are used by the frequency converter and determine the control parameter values for the selection of protective devices, as shown in equations 1 to 5.

Power: $\mathrm{P} = \mathrm{VI}$ (1)

Angular velocity: $\mathrm{w} = \mathrm{d}\beta/\mathrm{dt}$ (2) $\mathrm{w} = 2\pi/\mathrm{T}$ where T: period.

$\mathrm{w} = 2\pi\mathrm{f}$ (3) where f: frecuency.

$\mathrm{w} = \mathrm{n}\,(2\pi/60)$ (4) where n: revolutions per minute.

Torque: P/w (5)

The most commonly used controller in this application is known as PID, proportional, integral, and derivative, expressed in equation 6.

$$PID(S) = \left(k_p + \frac{k_d}{S} + k_s\right) e(S) \quad (6)$$

The proposed control is the fractional order proportional, integral, and derivative control, better known as Fractional Order PID (FOPID). The fractional order control satisfies equation 7.

$$FOPID(S) = \left(k_p + \frac{k_d}{S^{\lambda}} + k_i S^{\mu}\right) e(S) \quad (7)$$

For the integration of FOPID control into a digital device, the use of the Z-transform is required. Equation 8 represents the definition of the Z-transform of a sampled function f(kT).

$$F(Z) = \sum_k^{\infty} f(kt)\, z^{-k} \quad (8)$$

The most relevant formulas are the Z-transform of the derivative and the integral of a function, which are represented by Equations 9 and 10 [38]. These formulas enable working with block programming platforms.

$$Z\left\{\frac{df(t)}{dt}\right\} = \frac{1-Z^{-1}}{Tz^{-1}} f(Z) \quad (9)$$

$$Z\{\int f(t)dt\} = \frac{Tz^{-1}}{1-Z^{-1}} f(Z) \quad (10)$$

For the block programming, Simulink software was used due to its ease of programming systems in both the continuous domain (using the Laplace transform) and the discrete domain (using the Z-transform). The block programming is illustrated in Figure 3, which shows the block diagram for a control system programmed using Freescale technology with Simulink software.

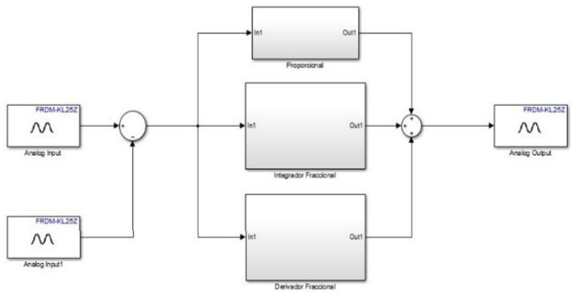

Fig. 3. Block diagram for FOPID system programmed in Simulink freescale technology.

For the validation of the control system, a fractional order control implemented in a PLC was used, and the results are presented in Figure 4. In the figure, it can be observed that when the system starts from rest and the Set Point value is set to 100°C, a ramp-up response is generated in the output until it reaches the Set Point value. The variations around the Set Point (noise) occur due to the phase change of water from liquid to vapor.

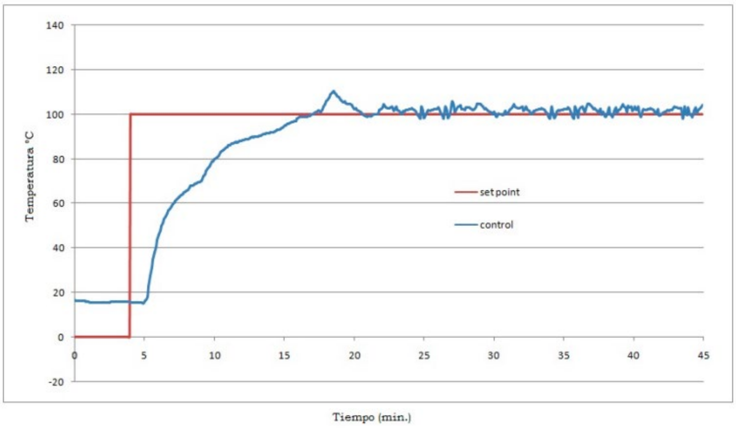

Fig. 4. Response graph for change of set point (ascent ramp).

Figure 5 shows the response to variations in the Set Point value. It is important to note that the response is acceptable in regions of stable temperatures, and the visually abrupt variations located in the higher steps are proportional to the effect of thermal inertia.

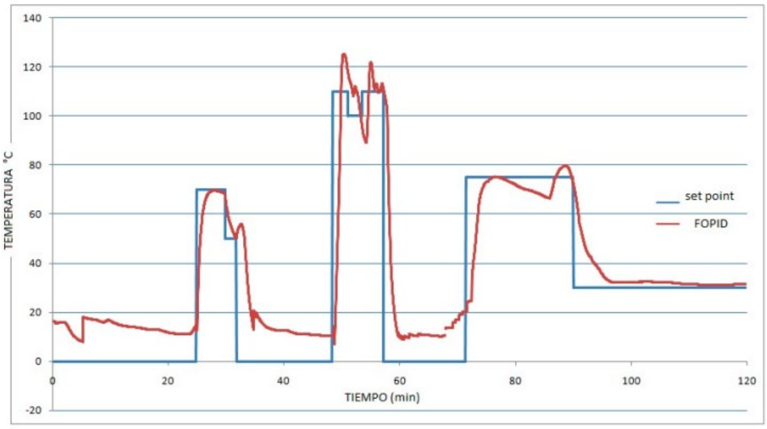

Fig. 5. Graph of real response to steam generation system.

The results are discussed in the following section.

4 Results

The control system for the solar-tracking CPC steam generator was tested from August to December 2017, yielding feasible results for solar energy tracking. Figure 6 shows the behavior of the ideal temperature versus the actual temperature obtained with the PLC and FOPID control. During the tests, steam and hot water were generated at temperatures ranging from 90°C to 110°C.

For this temperature range, the product obtained at the system output, both hot water (90°C) and steam (110°C), can be used for various purposes in domestic settings, such as cleaning, disinfection, or sterilization. In conclusion, this technological project, applied to solar energy utilization, carried out at the Technological University of Puebla, has a significant impact on helping to preserve the environment.

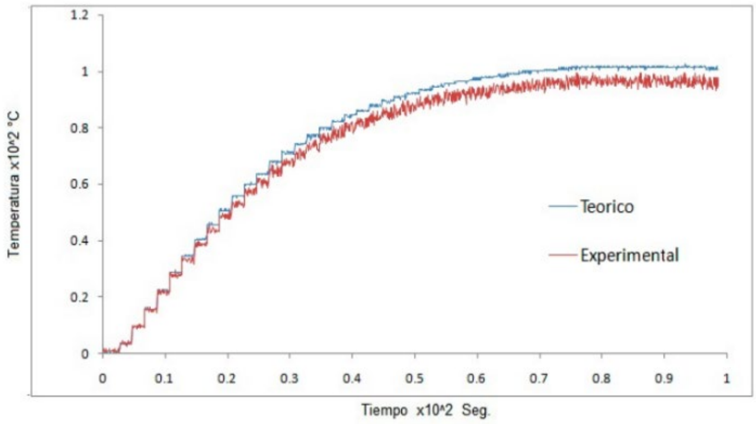

Fig. 6. Steam Generation System Operation Cha.

5 Conclusions

The advantage of fractional-order control, with a fractional-order derivative term in the range $0 < \mu < 1$, limits the control output when subjected to a step or impulse input.

The programming of control in digital devices, specifically PLC microcontrollers, can be done by developing algorithms in the C language or by using block programming platforms such as Simulink-Matlab. It is recommended to use C programming to minimize errors, while block programming can be utilized by experienced developers.

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