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Design and implement a solar tracker control algorithm for a photovoltaic module

Diseñar e implementar un algoritmo de control para el seguimiento solar de un módulo fotovoltaico

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Abstract

This paper presents the design of two control algorithms, for a one-axis and a tow-axis solar tracker. The solar position with a time correction through the Yallop's algorithm is estimated, in order to define the turn's freedom of the trackers. The mathematical model of the position's system and the mechanical structure of the solar trackers are obtained and two PID controllers are designed through the second tuning method of Ziegler-Nichols. The PID controllers designed are implemented in a microcontroller. This has a visualization stage, power stage, actuators and power and position sensors to close a control loop. The results that are obtained show that it is possible to maintain the output power of a photovoltaic module between a desired range when a solar tracker control algorithm is implemented.

Solar Position, Mathematical Model, Controller

Resumen

En este trabajo se presenta el diseño de dos algoritmos de control para seguidores de uno and dos ejes de libertad. Se estima la posición solar con una corrección de tiempo mediante el algoritmo de Yallop, con la finalidad de determinar la libertad de giro de los seguidores. Se obtiene el modelo matemático del sistema de posicionamiento and de la estructura mecánica de los seguidores solares and se diseñan dos controladores PID, mediante el segundo método de sintonía de Ziegler-Nichols. Los controladores PID diseñados se implementan en un microcontrolador con el desarrollo de las etapas de visualización de datos, acondicionamiento de señal, potencia, actuadores, sensores de potencia and posición solar para cierre del lazo de control. Los resultados que se obtienen muestran que es posible mantener la potencia de salida de un módulo fotovoltaico dentro de un rango de funcionamiento deseado al implementar un algoritmo de control para el seguimiento solar.

Posición Solar, Modelo Matemático, Controlador

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Introduction

Within the renewable energies, photovoltaic energy stands out. This is due to its independence from fossil fuels and low impact on the environment, it is positioned as an ecological alternative to counteract environmental problems that cause the generation of conventional energies (Faria and others, 2017). However, the efficiency of these systems is a matter of great concern among scientists, this is due to the losses by conversion of solar energy to electrical and environmental conditions, such as humidity, dust, shadows, temperature, angle and intensity of incident solar radiation (Sreewirote, 2017).

There are two types of photovoltaic, fixed and mobile systems. The fixed installations have an orientation and inclination depending on the place of installation. Within the mobiles, there are the solar trackers of an axis and of two axes. The first follow the movement of the sun from east to west and increase energy production by 20% compared to fixed installations. The second, in addition to following the solar position from east to west, also follow the solar height, so they increase energy production by 40% compared to fixed installations (Diaz & Carmona, 2015).

Current followers use algorithms that seek to position the horizontal energy capture surface to solar radiation. For example, in (Huynh & Dunnigan, 2016) and (Makhija, Khatwani, Khan, Goel & Roja, 2017), light sensors are used to determine the position of the surface, or in (Astanto, Prasetyandi, Purwadianta & Sambada, 2016), GPS technology is implemented to determine the position of the sun and to orient the catchment surface. However, these jobs do not have a feedback to control the power output of the system.

Unlike previous works, the design of a control algorithm for solar tracking is proposed; that positions the horizontal photovoltaic module to solar radiation, as long as the output power is below the nominal power of the module. The controller modifies the angle of incidence when the power is between ± 5% of its nominal value, this to keep the production of energy within this range as long as possible.

The purpose of implementing the control is to avoid damage due to overproduction of energy and prolong the useful life of the photovoltaic module.

To determine the solar position and modify the angle of inclination of the module, a light sensor is used; in addition to voltage and current sensors to calculate the output power of the system, in order to obtain feedback and close the PID control loop implemented in a microcontroller.

This work is developed in VIII sections. In section II, the solar position for a given point is estimated. The mathematical model of structures for solar tracking is presented in section III. Section IV describes the design of the PID control algorithm. The simulation graphs are shown in section V, in section VI the implementation is described, in section VII the results are presented, in section VIII the acknowledgments and in section IX the conclusions.

Estimation of solar position

To estimate the position of the sun with respect to the earth, two angles of interest are estimated, the hour angle (ω) and the solar height (α), shown in Figure 1 (Khatib & Elmenraich, 2016). This is done in order to know the freedom of rotation that solar trackers should have.

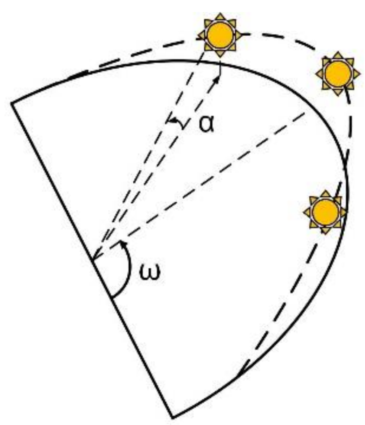

Figure 1 Solar height and hour angle
Source: (Khatib & Elmenraich, 2016)

It is considered that the standard time differs from the true solar time (Tsv), for which a time correction is made by means of the Yallop algorithm. This is chosen for its high precision for the years from 1980 to 2050 (Muneer, Gueymard & Kambezidis, 2004).

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$$T_{sv}=U_T+E_{TC}+\frac{1}{15}(L_{mel}+L_{Long}) \quad (1)$$

Where UT is the time in hours (hrs), ETC is the corrected time equation (hrs), Lmel is the local longitude meridian standard (°) and LLong is the meridian length of the observer (°). The hour angle is defined as the angular displacement of the sun from east to west, taking a local point as a reference. The solar height as the angular height of the sun measured from the horizontal (Muneer, Gueymard & Kambezidis, 2004). These angles are estimated by the equations:

$$\omega = \frac{15T_{sv}-(12\times 60)}{60} \quad (2)$$

$$\alpha = \text{asen}[\text{sen}(\varphi)\text{sen}(\delta_{dec}+\cos(\varphi)\cos(\omega) \quad (3)$$

Where φ is the latitude of the installation point in (°), and δ_{dec} is the decline considered at solar noon (°).

Modelado de sistema de seguimiento

The design of the two followers is done in SOLIDWORKS®. The device of an axis of freedom follows the hour angle (ω) with a fixed angle of inclination (β) of 24 ° (Figure 2). The follower of two axes of freedom (Figure 3), acts both for the hour angle (ω) and for the angle of the solar height (α).

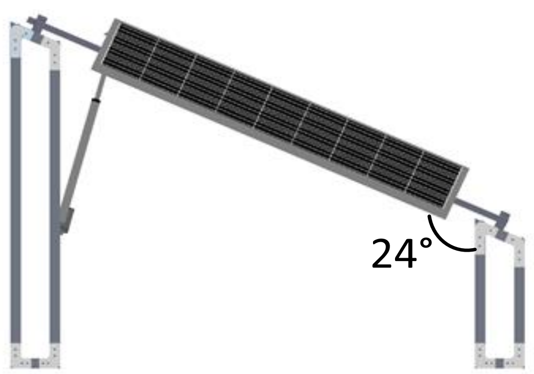

Figure 2 Follower of an axis of freedom
Source: Own Elaboration

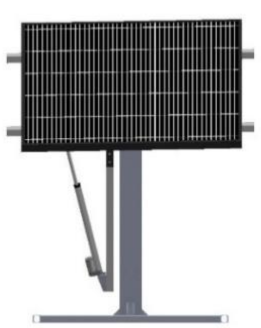

Figure 3 Seguidor solar de dos ejes de libertad
Source: Own Elaboration

The solar tracking system is made up of two parts as shown in Figure 4 (Utkin, Guldner & Shi, 2009). A positioning system and a mechanical system that replaces the mechanical structures shown in Figure 2 and Figure 3, where B1 and B2 represent the bearings, and J the moment of inertia of the photovoltaic module.

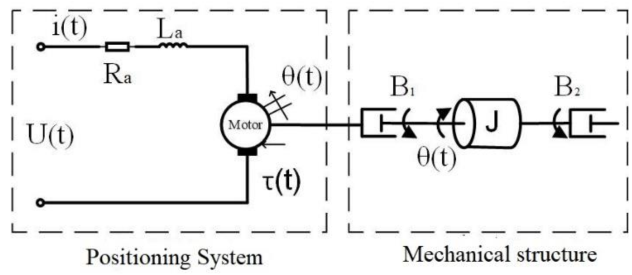

Figure 4 Solar tracking system
Source: Modified from (Utkin, Gundner 6 Shi, 2009) and (Ogata, 2010)

The mathematical model of the positioning system consists of a permanent magnet DC motor, which is governed by two equations, one electrical and one mechanical (Utkin, Guldner & Shi, 2009):

$$U(t)=R_a i(t)+L_a\frac{di(t)}{dt}+K_e\frac{d\theta(t)}{dt} \quad (4)$$

$$\tau(t)=J_1\frac{d^2\theta(t)}{dt}+B\frac{d\theta(t)}{dt} \quad (5)$$

The second law of Newton states that the algebraic sum of moments or pairs around a fixed axis is equal to the product of inertia by angular acceleration, therefore, the mathematical equation of the mechanical structure is (Ogata, 2010):

$$\tau(t)=J\frac{d^2\theta(t)}{dt}+B_1\frac{d\theta(t)}{dt}+B_2\frac{d\theta(t)}{dt} \quad (6)$$

By joining the equations (4), (5) and (6) and eliminating the viscous friction coefficients B1 and B2, we obtain the transfer function of the follower of an axis of freedom:

$$\frac{\theta(s)}{V(s)}=\frac{K_M}{s[(J_1L_a+JL_a)s^2+(J_1R_a+\ldots}$$

$$\ldots JR_a+BL_a)s+K_MK_e]$$

Where R_a is the armature resistance (Ω), La is the armature inductance (H), i (t) the armature current (A), θ (t) the position (°), K_e the electromotive force constant, τ (t) the torque, J the moment inertia of the photovoltaic module (Kg), J1 the inertia of the motor rotor (Kg) and B the viscosity coefficient (kg/s). The moment of inertia of the photovoltaic module is obtained by means of equation (8) (Jonhson, Mazurek & Eizanberg, 2010).

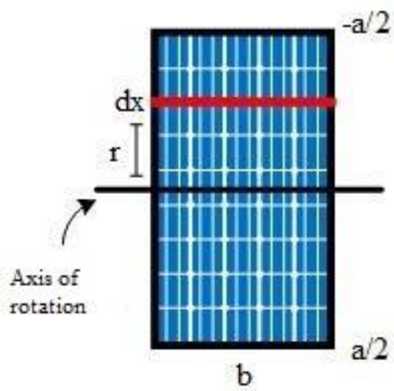

Figure 5 Moment of horizontal inertia.
Source: Own Elaboration

$$J_3=\frac{M_a}{b}\int_{-\frac{a}{2}}^{\frac{a}{2}} x^2\,dx \quad (8)$$

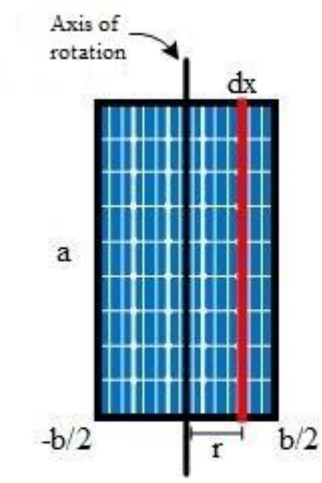

Figure 6 Moment of vertical inertia
Source: Own Elaboration

$$J=\frac{M_a}{b}\int_{-\frac{b}{2}}^{\frac{b}{2}} x^2\,dx \quad (9)$$

To obtain the mathematical model of the two-axis follower, each axis of freedom is considered as an independent system. In the system of the hour angle tracker, equations (7) and (8) are implemented. For the solar height tracker, equation (7) is considered, where the moment of inertia of the photovoltaic module is obtained with the equation (9).

I. Design of PID control algorithm

A PID controller is designed which is based on the scheme proposed by Ogata (2010), Figure 7. It has 3 tunable parameters, which are the proportional action K_P, the integration time T_i, and the derivation time T_d.

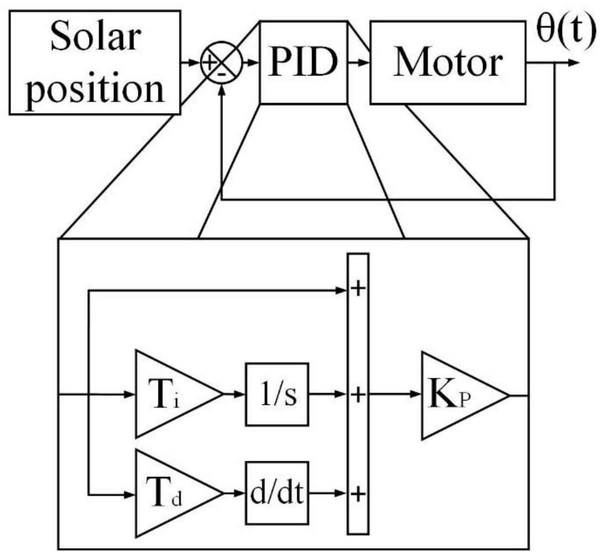

Figure 7 Block diagram of PID controller
Source: (Ogata, 2010)

$$PID= K_P\left(1+\frac{1}{T_i s}+T_d s\right) \quad (10)$$

The 3 parameters of the PID equation are calculated by means of the second Ziegler Nichols tuning method and equation (7). In addition, a manual tuning is performed to increase its accuracy (Ogata, 2010). The results are shown in Table 1, Table 2, and Table 3.

	Ziegler Nichols	Tuned
K_P	104.848	10.4848
T_i	5.048	0.05048
T_d	1.262	0.001262

Table 1 Hourly angle controller gains for an axis tracker
Source: Own Elaboration

	Ziegler Nichols	Tuned
K_P	235.3547	2.3535
T_i	14.1285	0.1413
T_d	3.5321	0.0035

Table 2 Solar height angle controller gains for two-axis tracker
Source: Own Elaboration

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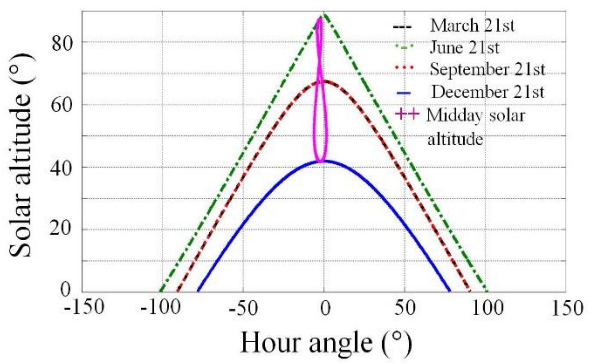
	Ziegler Nichols	Tuned
K_P	207.6485	2.0765
T_i	11.1032	14.1285
T_d	2.7758	0.0026

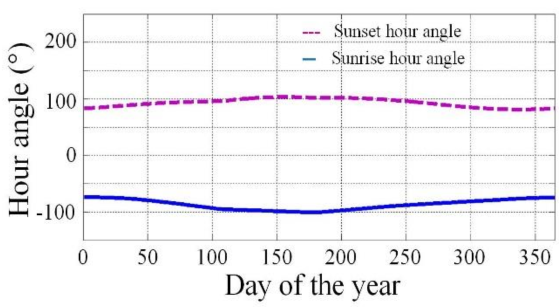
Table 3 Winnings of hour angle controller for two-axis tracker
Source: Own Elaboration

Simulations

With equations (1), (2) and (3), the solar height and the hour angle at dawn and sunset are estimated in the MATLAB® programming environment. The results shown in Graph 1 and Graph 2 are obtained.



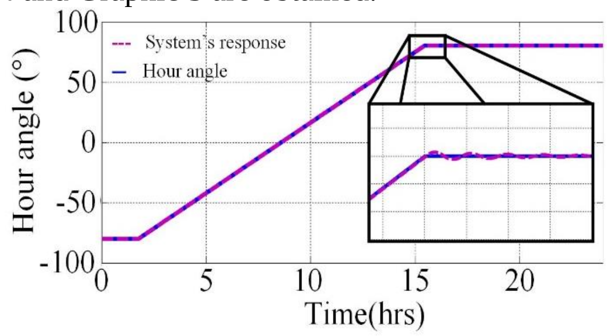
Graphic 1 Estimation of solar height
Source: Own Elaboration



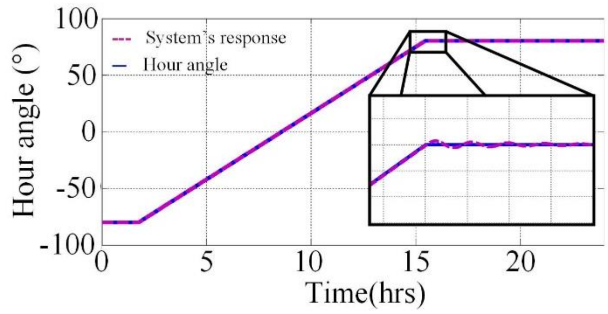
Graphic 2 Estimation of hour angle at dawn and dusk
Source: Own Elaboration

From Graphic 1, it can be seen that one must have a freedom from 0 ° to 90 ° to follow the solar height (90 ° is the horizontal). In Graphic 2, an average angle at sunrise of -87 ° and at nightfall of 92 ° is obtained. It is concluded that it should have an approximate freedom of -90 ° to 90 ° (where 0 ° is the horizontal). Three simulations are carried out in SIMULINK® to know the response of the tracking system according to the diagram shown in Figure 7. Equations (1), (2) and (3) are used to know the solar position, (8) for system dynamics and (10) together with Table 1, Table 2 and Table 3 for the PID controller

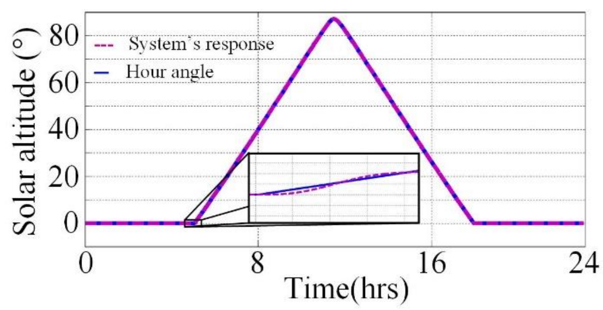
The results shown in Graphic 3, Graphic 4 and Graphic 5 are obtained.



Graphic 3 Follower controller response to an axis of freedom
Source: Own Elaboration



Graphic 4 Time angle controller response for two-axis freedom tracker
Source: Own Elaboration



Graphic 5 Solar height controller response for two axis of freedom tracker
Source: Own Elaboration

Graphic 3, Graphic 4 and Graphic 5 show the tracking systems that are modeled, are able to follow the trajectory of the solar height and the hour angle.

Implementation

The implementation of the solar tracking algorithm is based on the block diagram of Figure 8.

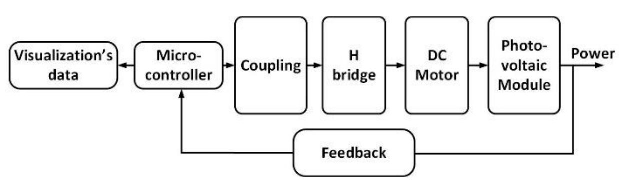


Figure 8 Implementation diagram
Source: Own Elaboration

The data display stage uses a 16x2 LCD screen, which shows the feedback variables such as: electric current (Honeywall, 2018), voltage, and radiation. A 16F2550 microcontroller (Microchip, 2004) is used, where the control algorithm (10) is programmed. For the control and power coupling stage, optocouplers 4N25 (TOSHIBA, 1998) and 2N2222A transistors (Semicon, 2013) are used.

A bridge H (Hart, 2011) with TIP31C transistors is designed to control the rotation of the XLA18 engine of the positioning system. In the follower of an axis a polycrystalline module is used and in the one of two axes an amorphous one, its specifications are shown in Table 4.

Parameter	Polycrystalline module	Amorphous module
P_{mp}	250W	135W
V_{mp}	30.2V	62.3V
I_{mp}	8.3A	2.17A
V_{oc}	37.8V	78.4V
I_{sc}	8.7A	2.52A

Table 4 Module specifications
Source: Own Elaboration

To measure the power produced by the photovoltaic module, the CSNE151 current sensor and the LV25P voltage sensor are used. To determine the solar position a light sensing device similar to that presented in (Huynh & Dunnigan, 2016), (Majhija, Khatwani, Khan, Goel & Roja, 2017) and as shown in the sample in Figure 9 is designed.

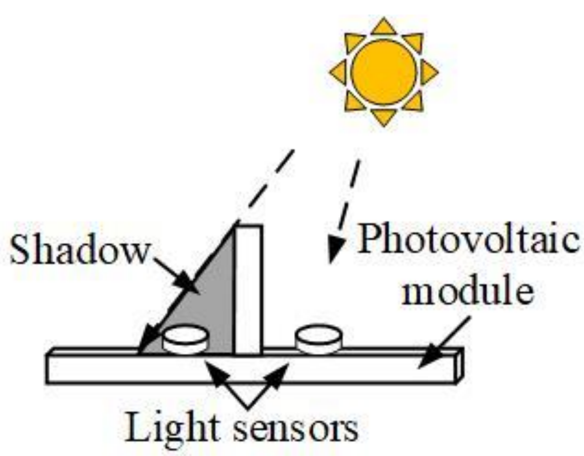
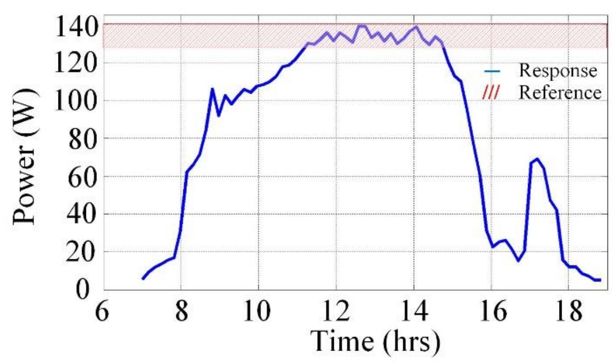


Figure 9 Solar position sensor
Source: Own Elaboration

Results

Test 1

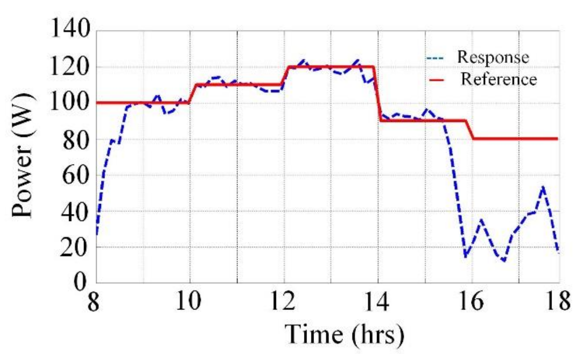
The objective of test 1 is to maintain the power of the amorphous photovoltaic module mounted on the two-axis follower by ± 5% its nominal power. The data sampling process is carried out on June 1 with a duration of 12 hours (7:00 a.m. to 7:00 p.m.), period in which power measurements are taken every 10min. The results are shown in Graphic 6.



Graphic 6 Test results 1
Source: Own Elaboration

Test 2

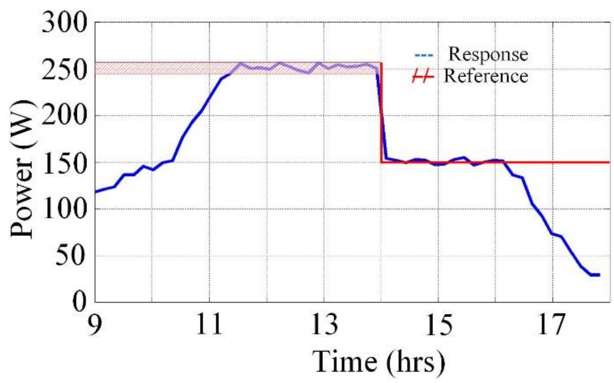
The objective of test 2 is to maintain the power of the amorphous photovoltaic module following a reference power. It is chosen randomly on June 2. The data sampling process lasts 10 hours (8:00 a.m. to 6:00 p.m.), period in which power measurements are made every 10min. The results are shown in Graphic 7.



Graphic 7 Test results 2
Source: Own Elaboration

Test 3

The objective of test 3 is to maintain the power of the polycrystalline photovoltaic module mounted on the follower of an axis in ± 5% of its nominal power from 9:00 am to 2:00 pm, from this time until 6:00 pm change the reference. It is chosen randomly on June 5. The data sampling process is for a period of 10 hours (9:00 a.m. to 6:00 p.m.), in which power measurements are made every 10min. The results shown in Graphic 8 are obtained.



Graphic 8 Test results 3
Source: Own Elaboration

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Conclusions

In the present work, the structures for one and two axes in the SOLIDWORKS® program were designed. In the development of the prototypes, the electrical signals of sensors and actuators were conditioned in order that the 18F2550 microcontroller interprets the data and controls the actuators in an appropriate way. A control algorithm programmed with CCS Compiler® is designed and implemented to read the signals transmitted by the sensors, interpret them and execute the control algorithm that decides the positioning of the photovoltaic modules based on the position of the sun and the power produced.

When analyzing Graphic 6, it can be seen that the photovoltaic module operates within its nominal range for 4hrs, from 11:00 AM to 3:00 PM. In the period from 15:40 to 17:00 hrs, there is an abrupt drop in production, this is due to shadows caused by the vegetation of the point. It is observed in Graphic 7, that the controller is able to make the power produced by the photovoltaic module follow any programmed reference.

In Graphic 8 it is observed in the period from 11:30 a.m. to 2:00 p.m., that the photovoltaic module operates within its nominal range, and from 2:00 p.m. to 4:00 p.m. follows the 150W reference, validating the correct operation of the controller.

It is possible to design a controller for the structure of one and two axes of freedom, which allows to maintain the production of energy within ± 5% of its nominal parameters in the peak hours of the day. It even manages to maintain a power less than the nominal, which opens the doors to these systems are scalable.

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