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ORIGINAL

Fuzzy control to maximize the performance of a two-degree-of-freedom photovoltaic solar tracker

Control difuso para maximizar el rendimiento de un seguidor solar fotovoltaico de dos grados de libertad

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ABSTRACT

Introduction: the need to reduce global warming is increasing every day and is a priority for the governments of our people and for organizations that support the environment, which is why it is proposed to contribute to increasing the performance of photovoltaic solar systems, using emerging technologies.
Method: for this work, control techniques are used through intelligent computing, more specifically a fuzzy control system for the search for the maximum power point in a photovoltaic solar tracker.
Results: as a result, a fuzzy controller was designed and implemented that allows obtaining the point of maximum solar efficiency at any time during the day. The solar tracker is oriented at the maximum power point (MPPT) at each instant in time, thus increasing energy production and reducing system losses due to the orientation of the PV panel.
Conclusions: the use of computational intelligence techniques such as fuzzy logic allows for an increase in the performance of photovoltaic solar tracking systems, which was verified by implementing a programmed fuzzy controller in an embedded system.

Keywords: Fuzzy Control; Photovoltaic Solar Tracker; Maximum Power Point Tracking (MPPT); Embedded System.

RESUMEN

Introducción: la necesidad en la reducción del calentamiento global aumenta cada día y es prioridad para los gobiernos de nuestros pueblos y de las organizaciones que, apuesta a favor del medio ambiente, por lo que se plantea contribuir al aumento en el rendimiento de los sistemas solares fotovoltaicos, habiendo uso de la tecnología emergentes.
Método: para este trabajo se hace uso de técnicas de control por medio de la computación inteligente, más específicamente sistema de control difuso para la búsqueda del punto de máxima potencia en un seguidor solar fotovoltaico.
Resultados: como resultado se logró diseñar e implementar un controlador difuso que permite obtener el punto de máxima eficiencia solar en cada momento durante el día. Se orienta el seguidor solar en el punto de máxima potencia (MPPT) en cada instante de tiempo, aumentando de esta manera la producción de energía y reduciendo las pérdidas del sistema por orientación del panel FV.
Conclusiones: el uso de técnicas de inteligencia computacional como la lógica difusa permite aumentar el rendimiento de los sistemas de seguimiento solar fotovoltaico, lo cual se logra comprobar por medio de un controlador difuso programado en un sistema embebido.

Palabras clave: Control Fuzzy; Seguidor Solar Fotovoltaico; Seguimiento del Punto de Máxima Potencia (MPPT); Sistema Embebido.

INTRODUCTION

The sun is one of the largest sources of energy in the universe and the planet, is used by humans in different ways and for many applications, one that has gained strength every day is the photovoltaic systems for power generation and its use to capture the radiant electromagnetic energy and heat from the sun.[1]

The Sun is the main source of the planet's energy. The temperature and pressure inside the Sun give rise to nuclear reactions that release enormous amounts of energy that reache the planet directly or diffusely reflected in the particles of the atmosphere, clouds, and other objects in the environment.[2] The availability of this energy depends on the geographical location of the place where it is to be harnessed. Figure 1 shows the places where there is the greatest potential for harnessing solar energy. Worldwide, solar PV will grow by 37 % by 2022, while solar PV production will average 6,2 % compared to 5 % in 2021. Asia is the country with the largest installation of PV systems with 64 % of all global capacity. Figure 1 shows the countries with the largest installed capacity in photovoltaic systems such as China, the United States, Brazil, India and Spain, while the countries that lead the markets in per-capital capacity are Australia, the Netherlands and Germany.[3]

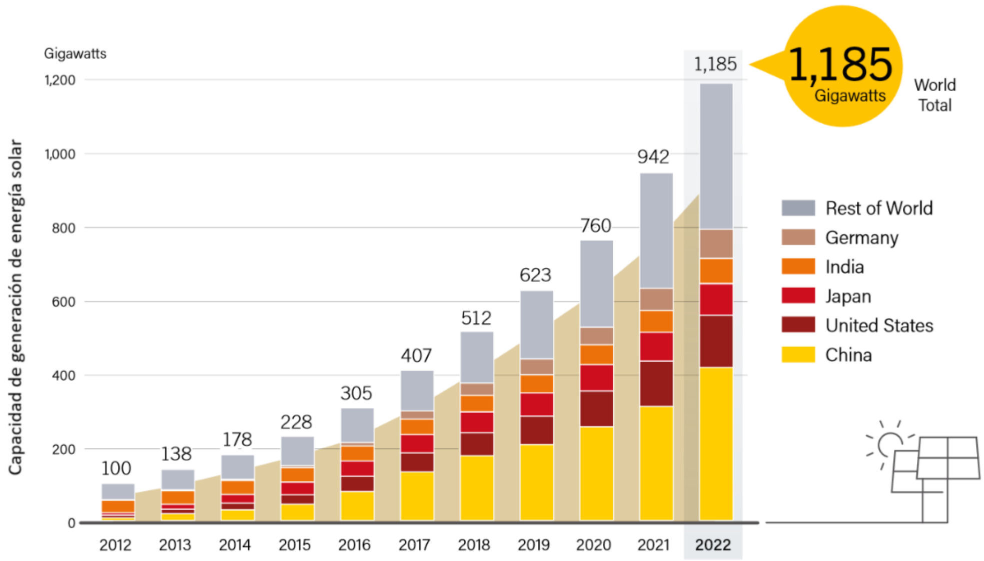

Figure 1. Evolution of photovoltaic E. production in the world[3]

Solar photovoltaic energy is one of the most widely used due to its ease of implementation and lower costs compared to other renewable energy sources such as wind, biomass and others. It is expected to reach 69,6 % of electricity generation by 2030. However, photovoltaic cells have an efficiency of about 25 % and the remaining energy is dissipated as heat.[4]

In 2017 the energy production capacity from PV systems was approximately 400 GW and is expected to reach at least 4500 GW by 2050. By 2022, an increase in PV installations of at least 240 GW is expected. The countries that contributed most to this growth are China, representing 44 % with approximately 106 new installations, followed by European countries with a new capacity of 39 GW, America also presents an increase of 18,6 GW as well as India with 18,1 GW.[5]

A photovoltaic solar panel can be constructed from monocrystalline, polycrystalline, amorphous and thin film silicon semiconductor material, among others. At conducted a study of different manufacturing plants of photovoltaic solar panels from several countries mainly Canada, China, Germany, India, Italy, Russia, Singapore, South Korea, Thailand, Taiwan, Ukraine, USA, to determine the best characteristics and parameters in the modeling of photovoltaic systems, giving a real vision for the performance of the panels that are currently on the market in these countries.[6] Figure 2 shows the results of the types of composition or material of which the analyzed photovoltaic panels are constructed.[6]

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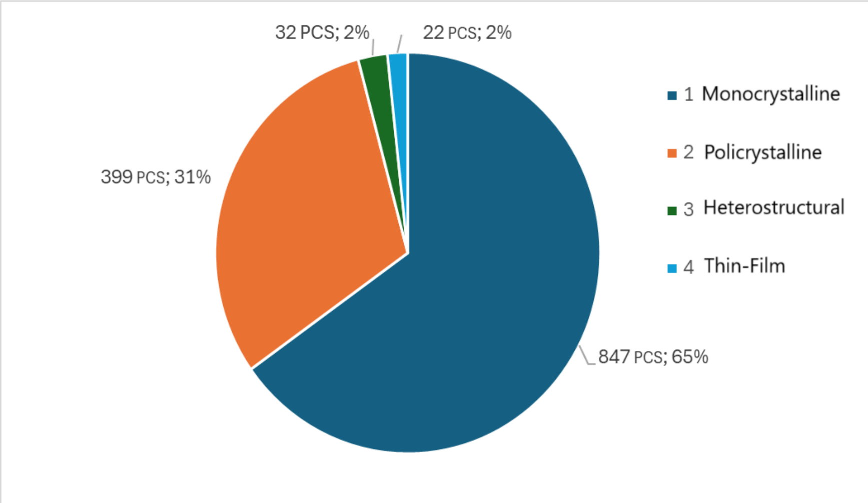

Figure 2. Type of photovoltaic panel composition

Solar tracking systems

Solar tracking systems aim to find the highest point of solar radiation to optimize such systems and increase efficiency.(7) Figure 3 shows a structure with eight photovoltaic solar panels on a solar tracking structure.

Figure 3. Structure with several solar PV panels

Photovoltaic systems are mostly installations where the photovoltaic panels are in a fixed orientation, i.e. they remain in the same position over time. A solar tracking system can be defined as a structure with a fixed and movable part that has a solar collection surface as perpendicular as possible to the sun throughout the day. There are two basic types of solar tracking systems which are: One-axis and two-axis systems.

Single-axis solar tracking system.

They consist of systems that have a degree of freedom of movement. There are three types of single-axis solar trackers: horizontal axis, azimuthal axis and polar axis.

Horizontal axis sun tracker: its surface rotates on a horizontal axis and in a north-south direction. The rotation is adjusted so that the normal to the surface coincides at all times with the terrestrial meridian containing the Sun.(8)

Sun tracker on an azimuthal axis: the surface rotates about a vertical axis; the angle of the surface is constant and equal to the latitude. The rotation is adjusted so that the normal to the surface always coincides with the local meridian containing the Sun. The rate of rotation is variable throughout the day. In figure 4 we observe a one-axis azimuthal type structure. Usually, the panel has a fixed zenith axis inclination of 45 degrees.

Solar tracker on a polar axis: the surface rotates on a south-facing axis inclined at an angle equal to the latitude. The rotation is adjusted so that the normal to the surface coincides at all times with the terrestrial meridian containing the Sun. The rate of rotation is 15° per hour, like that of the clock.(9)

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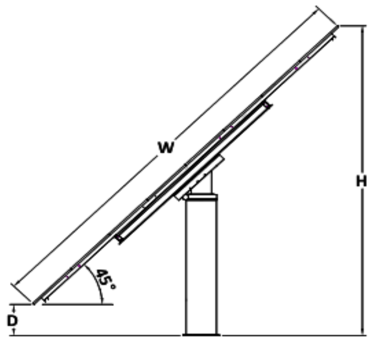

Figure 4. Single-axis solar tracker

METHOD

First, a review of the state of the art is carried out to obtain updated information on solar tracking systems applied to photovoltaic installations. The second step is to design a more adequate model of the tracking system considering the degrees of freedom of the mechanical structure of the solar tracker. Once the type of structure has been determined, the mathematical analysis of the controller is performed. Now it is necessary to perform the simulation of the controller and the PV cell array. After the controller design, a system is designed to obtain the maximum power point of the PV system. The third step is to perform the calculation and implementation of the system at scale, where the implemented controller is applied in an embedded system. Finally, performance tests and measurements are performed to determine the efficiency of the controller. In figure 5, the methodology used for the development of the work is described in a sequential diagram; this methodology allows a hierarchical order for a better development of the design and implementation of the whole system.[10]

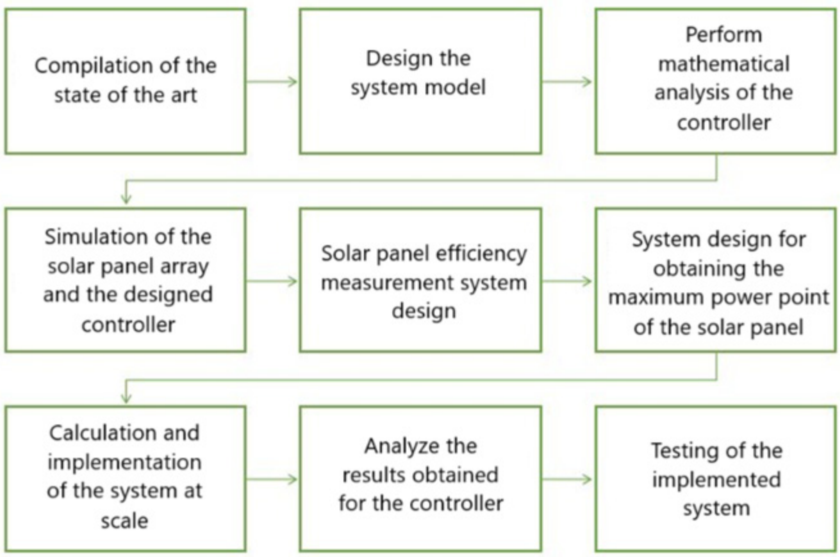

Figure 5. Methodology for work development

RESULTS

First, the design and implementation of a solar tracking structure on which the fuzzy controller must act is performed. For this work, a solar tracker with two degrees of freedom is selected for the azimuth and elevation movements. With these two movements it is possible to completely track the sun, taking into account that the highest solar energy collection or irradiation is achieved by placing the panel perpendicular to the sun.

The structure of the follower

In figure 5, the 50 cm high and 42 cm wide structure, made of acrylic in its largest proportion, is the support for the solar cells. The structure that supports the solar cells is moved by means of servomotors controlled by variable PWM. It has two servomotors that are responsible for moving the structure in the X and Y axes. It has a third motor that is responsible for the descent of the cells to increase the voltage difference, this descent of the cells is thirty degrees, this is done to have clearer data to track the maximum light intensity, once the central panel is receiving more radiation than the other four panels, these will be located parallel to the central panel and thus achieve that all panels can receive the greatest possible radiation.

Figure 6. Structure with the inclination of the solar panels

Sensor stage

The voltage sensing is a fundamental part because it gives the reference value that is then used as data for the controller, ie the input part to the control system, if there is a failure at this stage the controller does not work properly.[12]

Voltage Sensing

Solar cells were used, these cells are connected directly to the digital analog converter of the microcontroller, since they generate a maximum of 4,7 volts, which are not harmful to the microcontroller.[13] It is necessary to place current protection resistors between the sensors and the port, these resistors have values of 10 Kilo Ohms. Photovoltaic cells were used to be more precise since in most of the similar works they use photoresistors as sensors, this allows greater precision.[14] As can be seen in figure 7 there are five connectors for each of the cells, and has a cell called reference cell which is a point of comparison with the other four photovoltaic cells.[15,16]

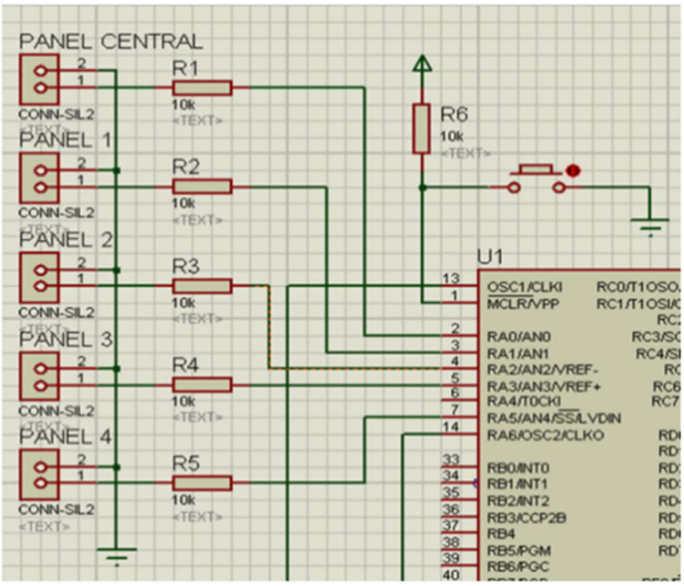

Figure 7. Proteus schematic of voltage sensing circuitry

Servomotors

For the movement of a solar tracker structure, medium and high-power direct current motors are commonly used, which are controlled by power electronics using PWM control signal mostly generated by a microcontroller.[17] Hobbico CS-60 Servo Standard Sport servo motors were used to perform the movement of each orientation.

The servomotors of movement in the X axis and Y axis rotate 180 degrees and the motor of location of the side panels with respect to the central panel rotates approximately 30 degrees the panels at the time of census of the highest light intensity, once the panel is located perpendicularly to the sun, the motor 3 will locate the side panels parallel to the central panel.[18] The angle of rotation of the servomotors is measured by measuring the voltage of their internal potentiometer, which varies between 0 and 2,5 volts depending on the angle. This variation between 0 and 2,5 volts can vary depending on the voltage variations in the power supply, as well as the type of servomotor being worked with.[19]

To measure the angle of the servomotors, the internal potentiometer that they contain was used, since by reading the voltage on the central pin of the servomotors, it is possible to know the position in which the servomotor is located. The voltages measured on the potentiometers of the servomotors at 0 and 180 degrees are shown in table 1.[20]

Table 1. Voltages measured on the servomotors at 0 and 180 degrees

Grades	Voltage (Servo Motor)	Voltage (Servo Motor)	Voltage (Servo Motor)
0	0,52 Volts	0,55 Volts	0,54 Volts
180	1,96 Volts	2,01 Volts	1,99 Volts

To calculate the voltage variation in the potentiometer for each angle that the servomotor rotates, equations 1 to 6 are used.

Motor 1 (X-axis motion motor):

$$\text{Voltage (1 degree)} = \frac{[1{,}97\text{V} - 0{,}52\text{V}]}{[180 - 0]} = 0{,}00805\ \text{V} \qquad (1)$$

Motor 2 (X-axis motion motor):

$$\text{Voltage (1 degree)} = \frac{[2{,}01\text{V} - 0{,}55\text{V}]}{[180 - 0]} = 0{,}00811\ \text{V} \qquad (2)$$

Motor 3 (Motor for positioning the side panels with respect to the central panel)

$$\text{Voltage (1 degree)} = \frac{[1{,}99\text{V} - 0{,}54\text{V}]}{[180 - 0]} = 0{,}00805\ \text{V} \qquad (3)$$

Knowing the voltage variation for each angle, we can calculate the position in which each of the servomotors are located with the following formulas:

Motor 1 (X-axis motion motor):

$$\text{Angle X} = \frac{[\text{Voltage(potentiometer)} - 0{,}52\text{V}]}{0{,}00805\text{V}} \qquad (4)$$

Motor 2 (Y-axis motion motor):

$$\text{Angle Y} = \frac{\text{Voltaje(potentiometer)} - 0{,}55\text{V}}{0{,}00811\text{V}} \qquad (5)$$

Motor 3. Motor location of the side panels with respect to the central panel.

$$\text{Angle Z} = \frac{[\text{Voltaje(potentiometer)} - 0{,}54\text{V}]}{0{,}00805\text{V}} \qquad (6)$$

The signals for servo control were generated by programming and not using the PWM modules of the microcontroller, since it only has two PWM modules. In the table 2, the time in milliseconds of the PWM signals for each of the servomotors to be positioned at 0 and 180 degrees can be observed.[21]

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Table 2. Duration in milliseconds of the half-cycles of the PWM signals

Grades	PWM (Motor 1)		PWM (Motor 2)		PWM (Motor 3)	
	High (ms)	Low (ms)	High (ms)	Low (ms)	High (ms)	Low (ms)
0	0,68	9,60	0,70	9,60	0,70	9,60
180	2,38	7,90	2,48	7.82	2,42	9,88

DISCUSSION

Design and implementation of the fuzzy controller

The mechanical structure of two degrees of freedom is where the fuzzy controller will be tested, which is designed based on the search or tracking of the MPPT maximum power point, and the technique used is that of perturbation and observation. The objective of the controller is to keep the structure always oriented towards the maximum solar energy collection, to optimize the autonomous photovoltaic systems and of obtain its maximum performance.[22,23]

Fuzzy logic

Fuzzy logic is an extension of traditional (Boolean) logic that uses concepts of set membership more similar to the human way of thinking. The concept of a fuzzy subset was introduced by L.A. Zadeh in 1965 as a generalization of a traditional crispsubset. Exact subsets use Boolean logic with exact values such as binary logic that uses values of 1 or 0 for its operations. In fuzzy logic, the process must be fuzzified with some membership functions which is where we introduce the input values we want to control and the output, which is our control signal, the rules with their respective connective either AND, OR, etc., then we introduce apply the most appropriate method of defuzzification.[24,25]

Fuzzy Control (FLC)

Rule-based fuzzy control expert systems, known as Fuzzy Logic Controllers (FLC), are undoubtedly the most widespread application of fuzzy logic. A fuzzy logic controller is a device capable of interpreting field signals and taking a consequent control action according to the information contained in its fuzzy rule base.[26,27] The core of an FLC consists of a processing brain in charge of making the necessary decisions to correct the value of the variable of interest. This structure can be seen in figure 8.

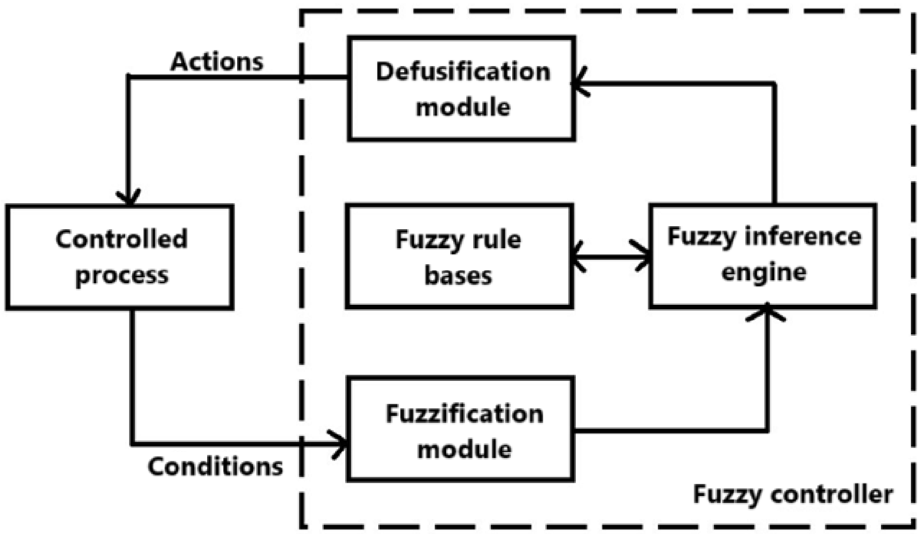

Figure 8. Schematic diagram of a controller based on fuzzy logic[28]

Fuzzy controller model

The function of the controller in a system is to elaborate the control action on the plant from signals that are passed to the plant input. The Fuzzy Logic Controller (FLC) uses the inference mechanism to elaborate such control action, which is called the “output” of the controller, while the dynamics of the plant are described implicitly by the implication rules, where the antecedent variables are the linguistic values of measured or observed magnitudes of the plant and are called “inputs” of the same.[29,30]

For the control system with a feedback loop, they are used as inputs:

The error

$$e(k) = \ Reference\!-\!Variablecontrolled\ (k) \qquad (7)$$

Error variation

$$e(k) = \ e(k) - e(k-1) \qquad (8)$$

The accumulated error

$$e_a(k) = \sum_{i=1}^{k} e(i) \qquad (9)$$

Where "k" is the sampling instant.

The problem of fuzzy control system stability has not yet found a solution. Guaranteeing the stability of nonlinear systems (any plant with a fuzzy controller is nonlinear par excellence) is a complicated problem, the analysis of which presents great difficulties especially because it does not admit generalizations.(31,32)

When designing a fuzzy controller, it is necessary to have a method for the comparison of functions and initialization of the rules, the critical points of a signal represent the most significant values in the characteristic curve before stabilizing the signal at the desired value, what is sought is to counteract the effect of the over impulses obtained in the output signal and configure the rules to obtain a stable signal and reach its set point. When 7 membership functions are handled in the input variables, we obtain 12 critical points which are reflected in the output action, and it is where greater intensity of over impulse occurs, it is advisable to characterize all the values obtained around the critical points in the rules, to obtain a more precise control and optimal output behavior.

Table 3. Rules of the north-south 3-input fuzzy controller

South Home Process End North	PG	PM	PP	Z	NP	NM	NG
	Z	B	MB	MB	MMB	MMB	MMB
	Z	B	B	MB	MB	MMB	MMB
	Z	B	B	B	MB	MMB	MMB
NG	A	Z	B	MB	MMB	MMB	MMB
	A	Z	B	B	MB	MMB	MMB
	MA	Z	B	MB	MB	MB	MB
	A	A	Z	B	MB	MMB	MMB
	MA	A	Z	B	B	MB	MB
	MA	MA	Z	B	B	B	B
NM	A	A	A	Z	B	MMB	MMB
	MA	MA	A	Z	B	MB	MB
	MMA	MMA	A	Z	B	B	B
	MA	A	A	A	Z	MMB	MB
	MA	MA	A	A	Z	B	B
	MMA	MMA	MA	A	Z	B	B
NP	MA	MA	MA	MA	A	Z	B
	MMA	MMA	MA	A	A	Z	B
	MMA	MMA	MMA	MA	A	Z	B
PG	MMA	MA	MA	A	A	A	Z
	MMA	MMA	MA	MA	A	A	Z
	MMA	MMA	MMA	MA	MA	A	Z

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Matrix of rules associated with the ideal controller with 3 inputs and one output, according to the process being worked on, where the 3 inputs must be compared concerning themselves and obtain a single NORTH-SOUTH output.

The controller will have as state or input variables the state of the North, South and Center cells.

Linguistic variable:

State of the solar cells (Voltage).

Fuzzy variables:

1. Large Negative (LN).
2. Negative Medium (NM).
3. Small Negative (NP). Zero (Z).
4. Positive Small (PP).
5. Positive Medium (PM). Large Positive (PG).

The same controller is used for the East-West movement.

The membership functions used for the design of the fuzzy controller in Matlab's FUZZY tool are shown below.

In figures 9 and 10 we can see the membership functions of the North cell state variable, which ranges from -3 to 3; this range was selected because it is the maximum practical voltage level of the cells. As mentioned before, seven membership functions were used for each of the inputs, in this case for the North cell input.

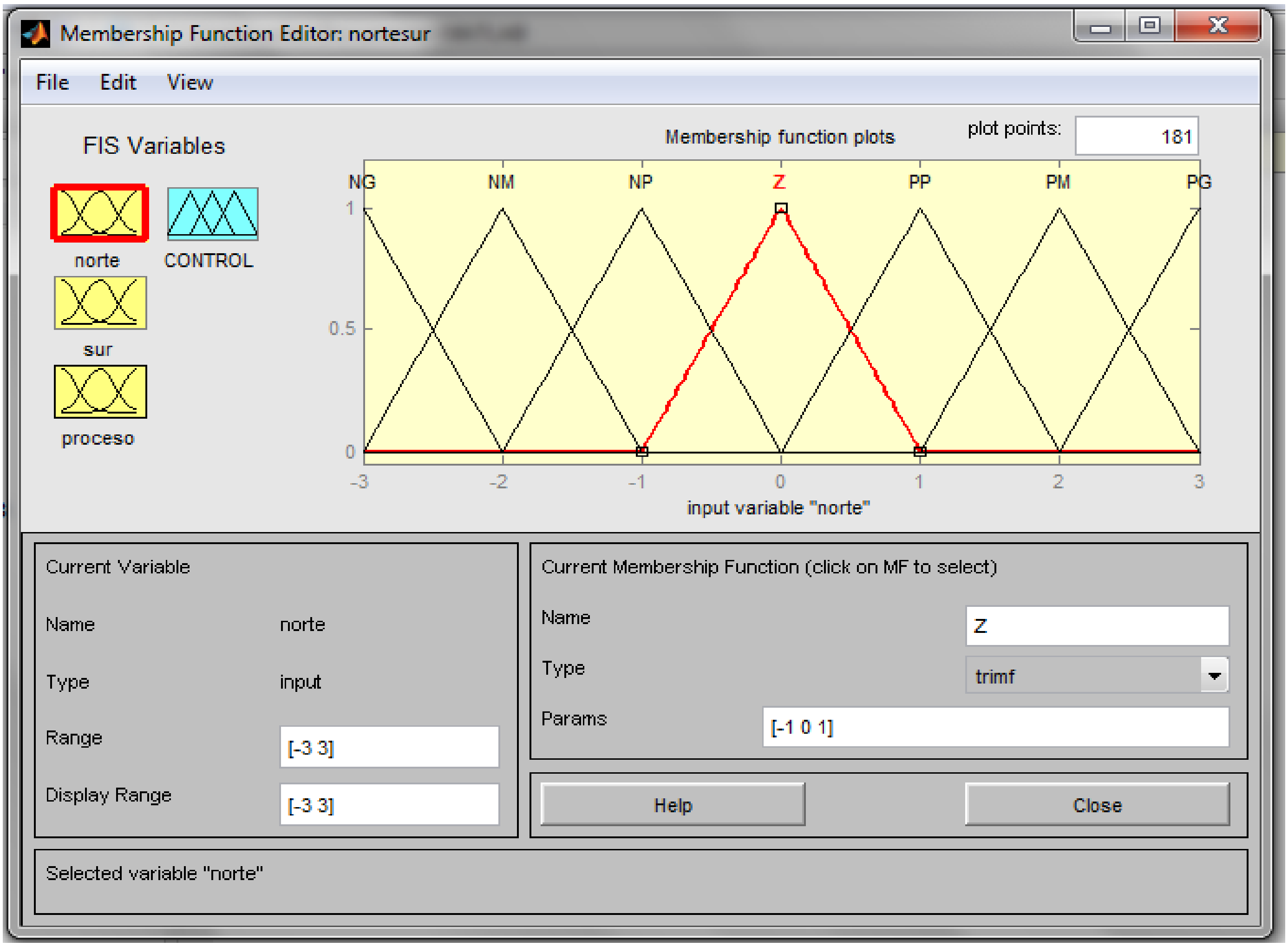

Figure 9. Membership functions for the variable North

With a total of 147 rules, the north-south controller for the photovoltaic system controls any signal captured with the sensors and provides great reliability when obtaining a control signal. The connective antecedent used is the AND that takes the minimum values between the membership functions, and the defuzzification method is the center of the area that calculates the values closest to the center of the junctions formed by the connective antecedent.

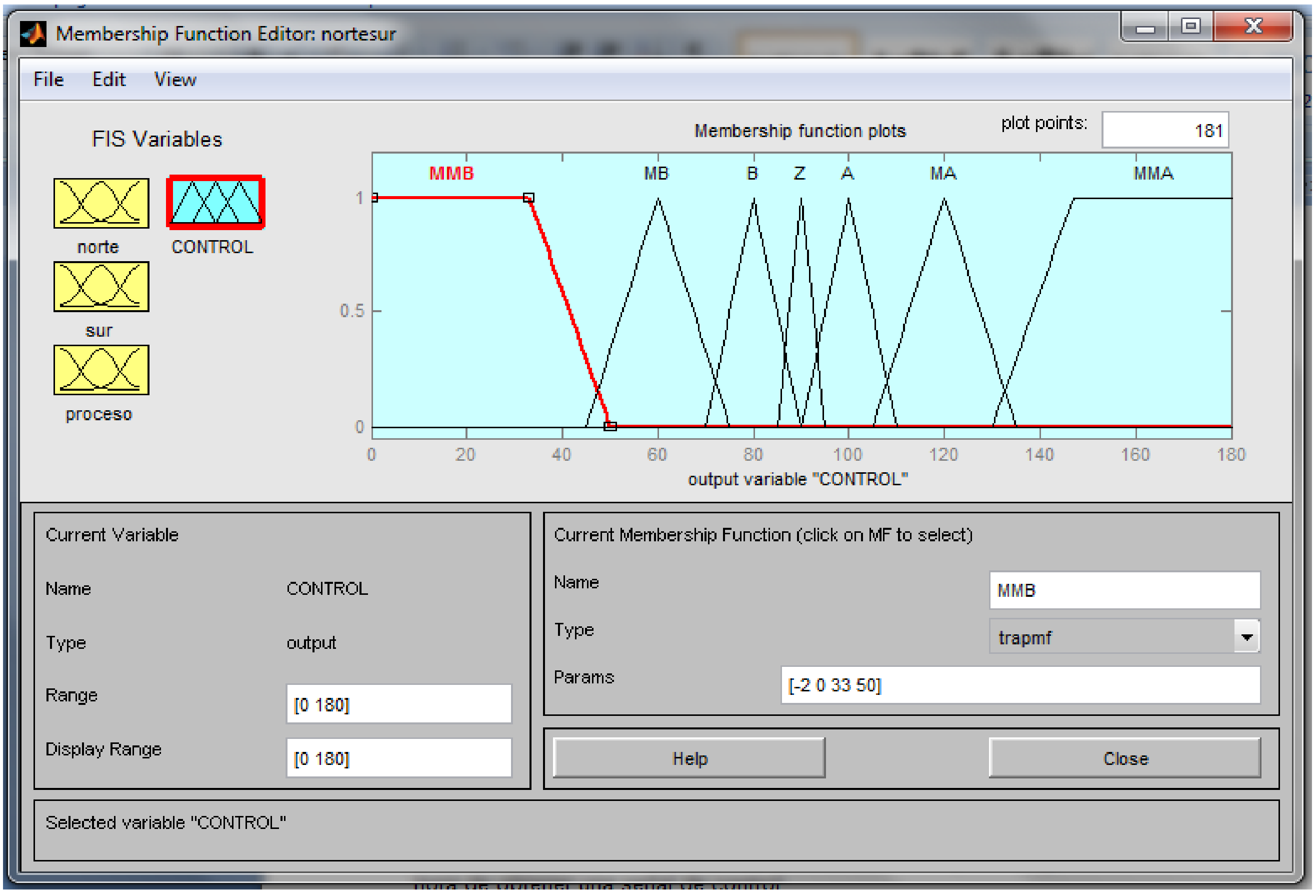

Figure 10. Funciones de membresía para la Salida de Control

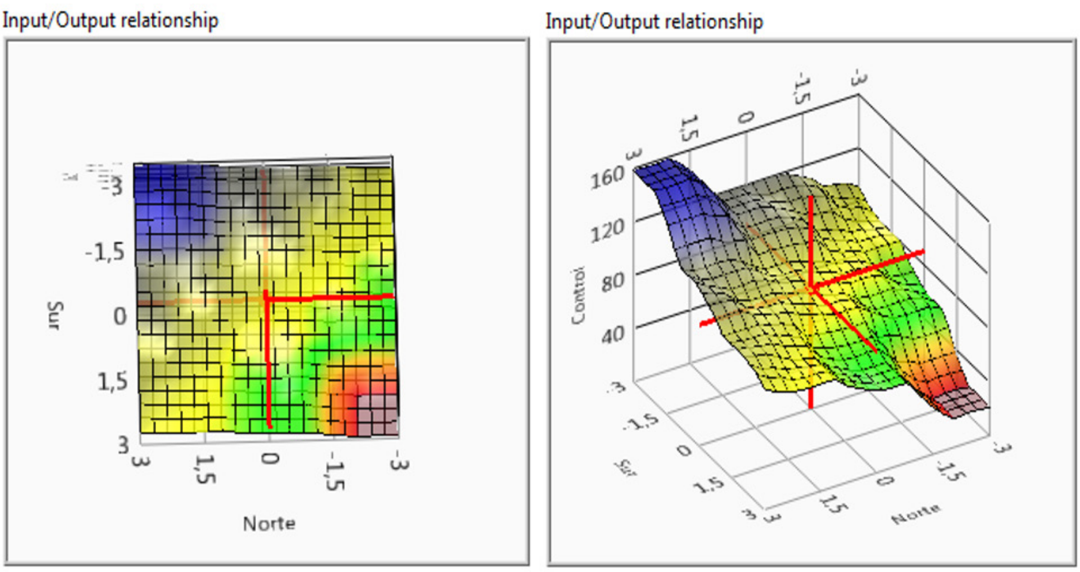

Figure 11. Controller response surface

Cell calibration

To start working with the system it is necessary to calibrate each of the solar cells to be used, to level the values and reduce the error. The procedure consists of obtaining the voltage of each cell at the same level of light radiation, which is usually a test performed in the absence of light. The procedure is to write down the values captured from each solar cell and then by software subtract or add that value in the controller. To capture the voltage values of the cells, a data acquisition card from National Instruments NI USB 6009 was used, and LabVIEW software was used to visualize the acquired data.[33] Figure 12 shows the data captured with the software and the acquisition board connected to the photovoltaic cells.

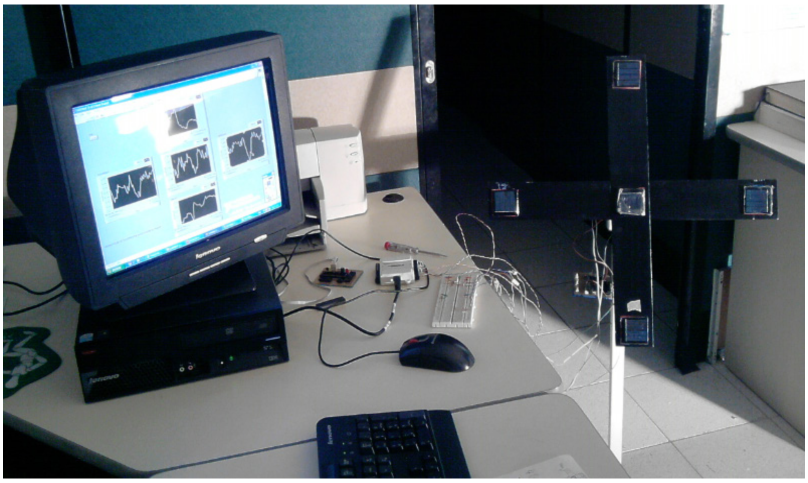

Figure 12. Acquisition software for calibration of Photovoltaic cells

The block diagram of the program developed in LabVEW for data acquisition is shown in figure 13.

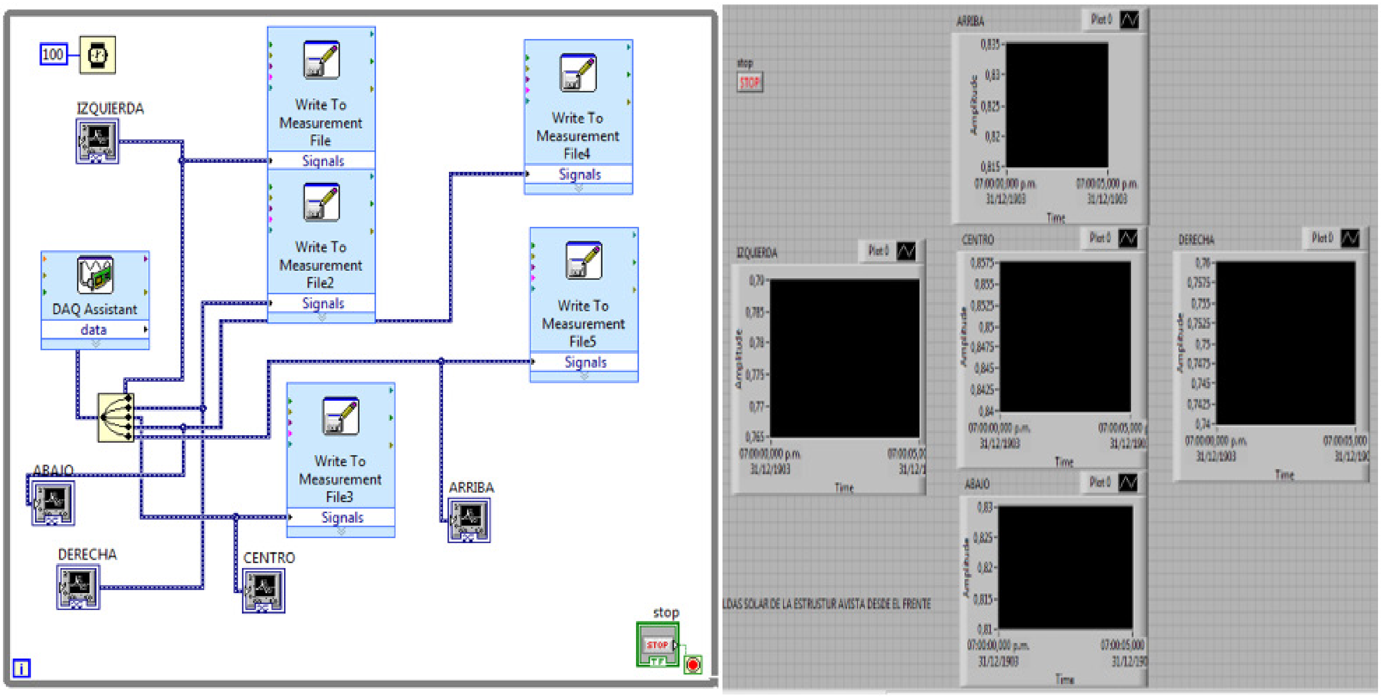

Figure 13. LabVIEW program of the ADQ system

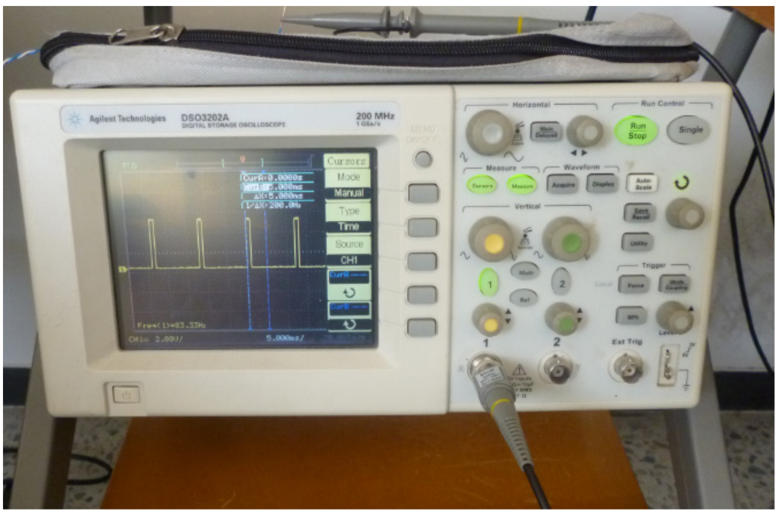

Figure 14. PWM signal at the start position

Figure 14 shows the PWM signal generated by the DSP to control the servo motor at different values when tracking the sun. The digital signal processing was implemented using an embedded system.[34]

CONCLUSIONS

Despite the efforts over the years that have been made to increase the performance of photovoltaic solar cells or modules, these still have a very low efficiency. Applications of this type lead to an increase in the performance and efficiency of the photovoltaic panels, since a direct tracking of the sun is performed so that the panel is oriented perpendicular to the sun and the maximum radiated energy is obtained. By using servo motors controlled by a PWM signal, the power consumption in the implemented system is reduced. Due to the tracking of the maximum power point, the power of the cells after positioning almost perpendicular to the irradiation source was the highest during the entire system run. The adjustment of the controller for simulation purposes was done by giving values to the inputs of the cells and as a result, different values of angles were obtained for the control of the servo motors, which corresponded to different time values for the PWM signal of the motors. The use of the fuzzy controller allowed the maximum power points using the signal values controlling the servo motors that precisely steer the robotic solar tracking structure.

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