Evaluation of Energy Efficiency in Photovoltaic Panels with Solar Tracker Based on Diffuse Control

Hipólito Carbajal-Morán[1,*], Javier F. Márquez-Camarena[2], and Carlos A. Galván-Maldonado[2]
[1] Control and Automation Laboratory, Universidad Nacional de Huancavelica, Huancavelica, Peru
[2] Department of Electronics, Universidad Nacional de Huancavelica, Huancavelica, Peru;
Email: javier.marquez@unh.edu.pe (J.F.M.-C.); carlos.galvan@unh.edu.pe (C.A.G.-M.)

***Abstract*—The objective of this work was to evaluate the efficiency of the energy produced by photovoltaic (PV) panels with solar tracker based on fuzzy control versus a fixed position PV panel with azimuth: −23.45° and elevation: 12.39°, in the city of Pampas-Tayacaja Huancavelica Peru at 3660 meters above sea level with a south latitude: 12. 39522° and west longitude: 74.87266°. An experimental prototype of a solar tracker was implemented, with an algorithm embedded in a PIC 18F4550 microcontroller; this microcontroller sends pulses to the longitudinal positioning motor driver and latitudinal positioning motor driver. The first motor, powered with 12 Vdc and current consumption of 1.5 A, produces the movement from east to west and vice versa; the second motor, with the same electrical characteristics as the first one, generates movements from north to south and vice versa. The data acquired from the light dependent resistive (LDR) sensors were sent by the microcontroller to the fuzzy logic controller implemented with the LabVIEW fuzzy system designer tool via USB communication. When evaluated, the efficiency of the PV panel with proposed fuzzy control, based tracker was higher in the clear or sunny day reaching 25.28%; and while in the cloudy day it was observed that the efficiency obtained is lower 8.97%, in both cases with respect to the fixed position PV panel. Therefore, it is concluded that the energy efficiency of the PV panel with the proposed solar tracker is always higher than that of the fixed position PV panel.**

***Index Terms*—Photovoltaic panel, solar tracker, diffuse logic, electric power generation**

Nomenclature

A	Ampere
ANFIS	Adaptive neural fuzzy inference system
CO_2	Carbon dioxide
DC	Direct current
FLC	Fuzzy logic control
I_p	Peak current
I_{sc}	Short circuit current
I_{pfp}	Peak current with fixed-position
I_{pft}	Peak current with fuzzy-tracker
kWh/m^2	Kilo Watt-hour per meter square
LDR	Light dependent resistance
PIC	Programmable integrated circuit
P_{pfp}	Peak power with fixed-position
P_{pft}	Peak power with fuzzy-tracker
PV	Photovoltaic
R_L	Load resistance
UV	Ultraviolet
V	Voltage
V_{dc}	Direct current voltage
V_p	Peak voltage
V_{pfp}	Peak voltage with fixed-position
V_{pft}	Peak voltage with fuzzy-tracker
W	Watt
Wh/m^2	Watt- hour per meter square

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Corresponding author: Hipólito Carbajal-Morán (email: hipolito.carbajal@unh.edu.pe).

I. Introduction

The global trend is to harness and use renewable energies that are abundant in nature, that do not pollute the environment, among these we have: wind energy provided by the wind, hydraulic energy provided by water and solar energy provided by the sun, with many others in development as evidenced by Cantarero [1]. Due to its origin, solar energy is practically an inexhaustible source for obtaining energy resources [2], and it can be used anywhere inside and outside the planet.

Solar radiation is defined as the flow of energy that we receive from the Sun in the form of electromagnetic waves that allow the transfer of solar energy to the Earth's surface [3]. These electromagnetic waves are of different frequencies and approximately half of those we receive are between the wavelength ranges of 0.4 µm and 0.7 µm, can be detected by the human eye, constituting what we know as visible light. Of the other half, most is in the infrared part of the spectrum and a small part in the ultraviolet [4].

Irradiance also known as insolation is the amount of solar energy received during a certain period of time, the unit of measurement with which it is represented is the Wh/m^2, in hours of peak radiation the irradiance can reach 1 kWh/m^2, the generation of solar energy in photovoltaic panels depends on their efficiency and position; due to its different behaviors, irradiance has three components: direct, diffuse and reflected [5]. Direct is that which is received directly from the Sun in a straight line, without being deflected in its passage through the atmosphere, it is the largest and most

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important in photovoltaic applications; diffuse is that which comes from the Sun after being deflected by atmospheric dispersion, it is that which is received through the clouds, as well as that which comes from the blue sky, if there were no diffuse radiation, the sky would look black even during the day, as happens with the moon; reflected: it is the direct and diffuse radiation that is received by reflection on the ground or other nearby surfaces. Global irradiance is the total radiation incident on a given surface represented by the sum of direct, diffuse and reflected irradiance.

The scaling up of renewable energies is determined by wind and solar energy, which represent more than 90% of the renewable energies produced in the world. This scaling up is mainly due to the deductions given by the different governments worldwide for the low environmental impact [6]. China, continues to lead this type of effort worldwide with a rapid increase in the deployment of wind and solar photovoltaic (PV) systems, this is due to a substantial reduction in the cost of installation and rapid advances in solar energy technology. On the other hand, in the United States, the installation of solar power generators is on the rise, offering significant advantages, such as reduced carbon emissions, greater diversification of energy supply, and sustainable energy independence [7]. In Latin America and the Caribbean, mainly in countries such as Nicaragua, Brazil, Argentina, Chile and Peru, the growing development of photovoltaic energy stands out, allowing the electrification of homes, health facilities and educational institutions in remote or difficult to access communities; one of the benefits being the substitution of the use of traditional fuels such as firewood, avoiding deforestation and reducing CO_2 emissions [8]. Also, in areas north of the equator as Malaysia and Iran have high temperatures and rainy environment with medium to high radiation throughout the year allowing the successful supply of photovoltaic energy [9]. Likewise, Alhousni *et al*. reviewed the existing solar energy potential in different Asian countries such as Oman and Dhofar [10], where the maximum radiation power is around 1360 W/m^2 is evident.

In the Andes area of Peru, lighting is promoted with local photovoltaic installation; also, the heating of houses with photovoltaic energy and passive bioclimatic solar designs are proposed [11]. On the other hand, the efficiency of obtaining electrical energy from photovoltaic panels is dependent on the position in front of the solar radiation, an orthogonal position will allow the capture of more electrical energy, so it is necessary to implement an electromechanical device that automatically tracks the movement of the sun throughout the day to maximize the exposure of solar panels to sunlight. This is achieved through the use of sensors and motors that orient the panels in the proper direction. Solar trackers are more efficient than fixed panels and can increase energy production considerably depending on the season of the year [12], therefore, the analysis of the behavior of solar trackers with different controllers, especially fuzzy for electric power generation, is necessary.

The universally used fuzzy controllers are of the Mamdani or Takagi-Sugeno type [13], with the Mamdani being compact and computationally more efficient in applications on the LabVIEW platform as evidenced by Vinogradov *et al*. [14]. The DC motor control implemented with this rule-based controller can be optimized with the combination with classical controllers, improving significantly in the rotation of electromechanical actuators [15]. Likewise, it is necessary to analyze the efficiency of solar trackers, estimating the highest potential solar incidence on a photovoltaic panel, by means of a prototype solar tracker [16], achieving optimal monitoring and tracking of the sun's radiation using inexpensive sensors such as LDR or photodiodes [17, 18]. Therefore, the objective of this work was to implement a solar tracker with a fuzzy controller and interface in the LabVIEW platform that allowed to demonstrate the improvement of the electric energy production with respect to a photovoltaic system with fixed orientation.

II. Related Work

Several works were carried out with trackers to harness solar energy, these solar trackers can be single-axis or dual-axis [19]; dual-axis trackers allow the photovoltaic panels to be positioned both in longitude and latitude and to remain orthogonal to the solar radiation allowing to optimize the capture of solar irradiance [20]. In addition, the control systems of these trackers can be feedback or non-feedback, so there are sensorless and sensor-based systems.

The solar trackers without feedback do not require sensors and have open control loop. Zhu *et al*. presented a solar tracker based on geometric sun-earth relationships with a projected solar radiation model [21]. Likewise, Vargas *et al*. [22] showed the construction of a low-cost photovoltaic kit for education, emphasizing the use of a linear model that feeds the algorithm that controls a solar tracker, they reported an energy improvement of about 32%. Kuttybay *et al*. [23] realized an hourly solar tracker for applications in different weather conditions; this single-axis solar tracker showed better performance on cloudy and rainy days. Fernandez *et al*. [24] implemented an optimized tracking strategy with backward focus to not create shadows in solar trackers with which the energy production was 1.31% higher than that generated by solar panels with astronomical tracking. Also, Cruz *et al*. [25] proposed a two-axis solar tracker methodology based on irradiance data, combining fuzzy models and day-hour relationships, reported that they present an energy advantage that exceeds 20% with respect to fixed photovoltaic panels. Fathabadi [26] proposed a novel high precision sensorless dual-axis solar tracker controlled by the maximum power point tracking unit available in almost all PV systems, this is a closed loop system using the actual direction of the sun to track being the main contribution of the work, this implemented PV system allowed the increase of energy harvesting from 28.8% to 43.6% weather dependent. AL-Rousan *et al*. [27] proposed two new intelligent solar tracking control systems based on the Adaptive Neural Fuzzy Inference System (ANFIS) principle of one and two axes to increase the performance of solar trackers, accurately predict the sun trajectory across the sky and minimize the error, thus maximizing the energy production of the solar tracking systems; by evaluating the ANFIS models, it is found that the proposed controllers are optimal for controlling solar tracking systems by predicting the solar angle to track based on the date and time.

Feedbacked solar trackers require sensors and have closed control loop, so they are able to generate real-time correction to keep the PV panels orthogonal to the solar radiation. Jamroen *et al*. [28] proposed a novel dual-axis solar tracking system feedbacked with four ultraviolet (UV) sensors to improve tracking to the solar path as well as photovoltaic power production; the tracking was performed by the pseudo-azimuthal mounting structure, which tracks the daily solar angle and respective elevation, obtaining an increase of generated power of 19.97% with respect to a fixed plate and 11% with respect to LDR-based solar tracking system. Acaroğlu *et al*. [29] presented a novel proposal to develop an efficient operation of solar power system augmentation with increasing high voltage direct current transmission systems as an alternative energy solution to meet energy demands in the context of a growing economy, and can be considered as a reference for works with photovoltaic electric power generation systems. Batayneh *et al*. [30] used four small photovoltaic cells as photosensors mounted on a photovoltaic module at four locations. The inputs retrieved by the photovoltaic cells were processed in a fuzzy logic system to track the trajectory of the sun. Seme *et al*. [31] designed a dual-axis solar tracker using four LDRs to track the sun's trajectory. Likewise, Hoffmann *et al*. [32] reported a dual-axis solar tracker with LDR sensors to adjust the panel orientation from electronic devices, obtaining monthly electrical power improvements of 17.20% to 31.10% with respect to a fixed position PV panel. Likewise, Perez *et al*. [33] when comparing the power obtained by a photovoltaic panel with a two-axis continuous motion mechanism with a solar tracker versus a fixed panel, achieved a 17% power gain with the use of the solar tracker. Apparently, the two-axis trackers are more efficient and are the most promoted to contribute to the saving of electric energy and to the possible mitigation of climate change, having improvements in the production of electric energy, with respect to static panels [34].

III. Materials and Methods

A. Requirements

For the implementation of the solar tracker different materials were used: two photovoltaic panels which are devices that convert the energy coming from solar radiation into electrical energy Hernández-Callejo *et al*. [35], these panels were made of polycrystalline silicon, with the following technical characteristics: peak voltage (V_p)= 18.25 V, open circuit voltage= 21.96 V, maximum power= 80 W, efficiency of each cell: 15.62%; efficiency of the whole panel: 13.23%, optimum operating current= 4.38 A, short circuit current (I_{sc})= 4.69 A, number of cells: 36, temperature: –40 °C to 85 °C, panel dimensions = 90.5 cm × 66.8 cm × 3.5 cm and weight = 7. 2 kg; 12 V and 1.5 A DC motors; Microchip PIC 18F4550 microcontroller [36], which allowed USB communication to a laptop computer with LabVIEW and Fuzzy Logic Toolkit where the fuzzy logic controller was implemented [37].

The method used was the experimental one, being the prototype the one that allowed obtaining data from the experimental group; represented by the energy generated by the panel with solar tracker based on fuzzy control. The control group was represented by the energy generated by the solar panel with fixed position; both installed in the Faculty of Electronic Engineering-Systems of the National University of Huancavelica, city of Pampas-Tayacaja in the Huancavelica region of Peru at 3660 meters above sea level at latitude south: 12.39522° and longitude west: 74.87266°.

B. System Model

The solar tracker with fuzzy logic controller, with which the experimental data were acquired, was implemented for the evaluation of energy efficiency, which consists of three main parts: sensor, fuzzy logic controller and actuators. Fig. 1 shows the structure of the proposed solar tracker, as well as the photovoltaic panel with fixed position, with azimuth: –23.45° and elevation angle to the north of 12.39°.

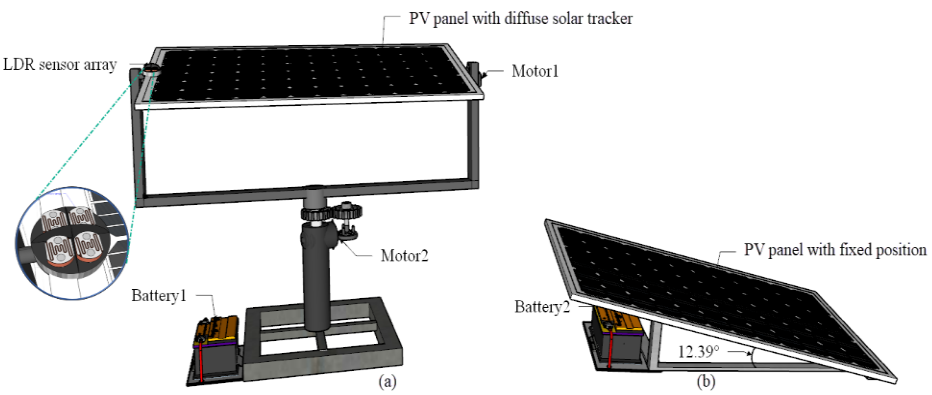


Fig. 1. (a) Structure of the proposed solar tracker and (b) photovoltaic panel with fixed position.

The LDR sensors detect the movement of the sun through the potential difference generated by the established array. The sensors that allow the rotation are constituted by LDR1 and LDR2 that generate alignment to the solar rays according to the array established in Fig. 2. This array uses the LDR1 as a reference to determine the location of the Sun allowing the fuzzy controller to determine the movement of Motor1 in the direction from east to west or vice versa indicated by the LDR2, to realign the photovoltaic panel. The angle "a" corresponds to the blind spot of the sensor, it depends on how much the LDRs are illuminated and depends on the distance between the LDRs and the radius of the semicircular sheet used as a shadow generator which allows the system to maintain the accuracy of the sun tracking despite solar disturbances and solar declination.

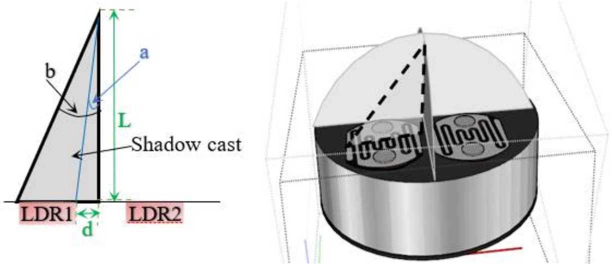


Fig. 2. (a) Array of LDR1 and LDR2, (b) semicircular sheet shadow generator.

In Fig. 2 (a), the angle a=arctan(d/L) was calculated, the angle b=arctan((d + diameter LDR)/L), corresponds to the angle that the rotational solar tracking LDR1 generates when fully shaded. In this work the radial length L=145 mm and d=3 mm, thus obtaining the angle a in Eq. (1):

$$a = \arctan\left(\frac{3}{145}\right) = 1.18° \tag{1}$$

As the LDR sensors used have a diameter of 6 mm, the angle b will be 3.55º, obtained by

$$b = \arctan\left(\frac{9}{145}\right) = 3.55° \tag{2}$$

Likewise, the sensors that allow generating the translation movement are constituted by the LDR3 and LDR4 sensors, whose configuration is orthogonal to the configuration of the rotation sensors indicated in Fig. 2. The shadow generator has the same semicircular shape as the one used with the sensors that allow generating the rotation movement by means of the driver, allowing the rotation of the Motor2 in the north-south direction or vice versa.

The operating principle of the controller is based on Fuzzy Logic Control (FLC) closed-loop rules which allowed to measure, compare and then act by positioning the photovoltaic panel orthogonal to the solar radiation; this being a characteristic of any process controller, as indicated by Patrick *et al.* [38]. The FLC implemented in the LabVIEW platform makes the inference of the signals according to the established rules for both longitudinal and latitudinal motion, sending as a response a signal for the motors to rotate in the north-south or east-west direction, positioning the photovoltaic solar panel so that it is orthogonal to the solar rays. The block diagram of the whole process of the fuzzy solar tracker is shown in Fig. 3.

The fuzzy logic latitude controller for the north-south rotation of the PV panel is designed using the Mamdani type control [39], which is feasible to use in this type of applications, as indicated by De Silva [40]. Considering the position of the north and south solar trajectory as two inputs, the inference engine for the control is based on 09 rules as follows:

1. *IF 'Sensor_LDR1' IS 'Low' AND 'Sensor_LDR2' IS 'Low' THEN 'Motor1' IS 'Stop'*
2. *IF 'Sensor_LDR1' IS 'Low' AND 'Sensor_LDR2' IS 'Medium' THEN 'Motor1' IS 'Turn_middle_right'*
3. *IF 'Sensor_LDR1' IS 'Low' AND 'Sensor_LDR2' IS 'High' THEN 'Motor1' IS 'Turn_right'*
4. *IF 'Sensor_LDR1' IS 'Medium' AND 'Sensor_LDR2' IS 'Low' THEN 'Motor1' IS 'Turn_middle_left'*
5. *IF 'Sensor_LDR1' IS 'Medium' AND 'Sensor_LDR2' IS 'Medium' THEN 'Motor1' IS 'Stop'*
6. *IF 'Sensor_LDR1' IS 'Medium' AND 'Sensor_LDR2' IS 'High' THEN 'Motor1' IS 'Turn_middle_left'*
7. *IF 'Sensor_LDR1' IS 'High' AND 'Sensor_LDR2' IS 'Low' THEN 'Motor1' IS 'Turn_left'*
8. *IF 'Sensor_LDR1' IS 'High' AND 'Sensor_LDR2' IS 'Medium' THEN 'Motor1' IS 'Turn_middle_left'*
9. *IF 'Sensor_LDR1' IS 'High' AND 'Sensor_LDR2' IS 'High' THEN 'Motor1' IS 'Stop'*

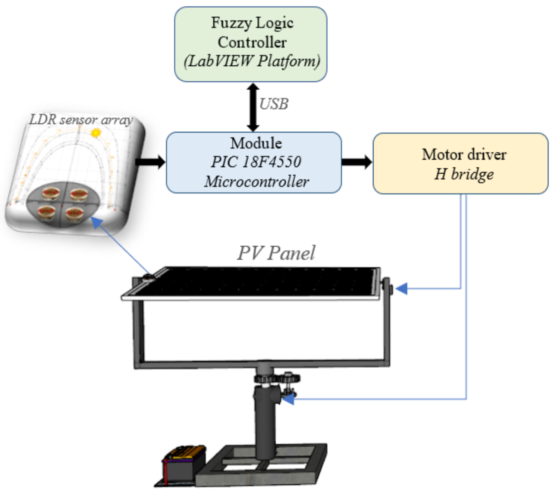
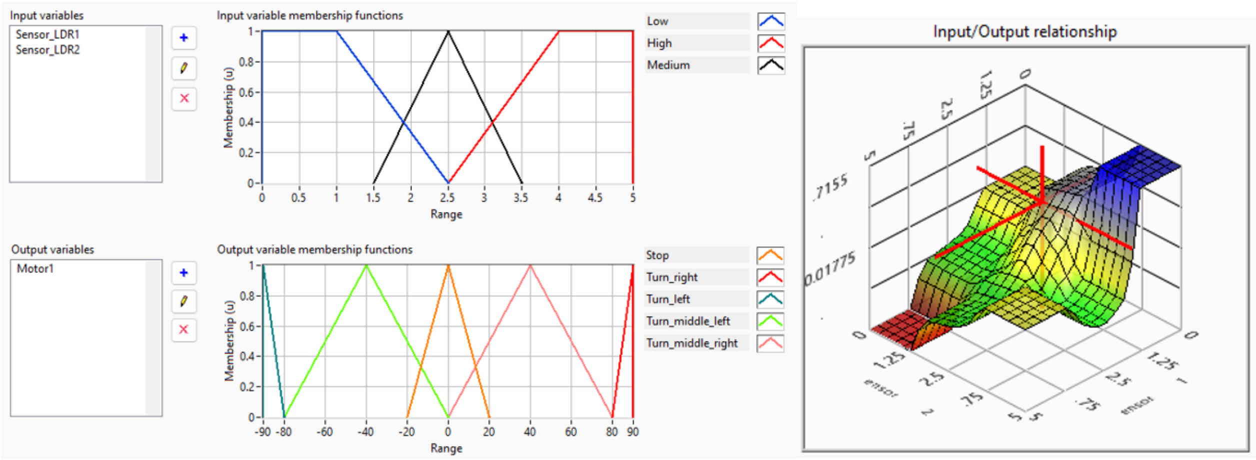


Fig. 3. Block diagram of the solar tracker with fuzzy controller.

The response to these rules input/output variable membership functions is shown in Fig. 4 (a) and the input/output relationship to them in Fig. 4 (b) that were implemented with the fuzzy system designer tool of LabVIEW, allowed the rotation from –90° to 90° of the "Motor1" that controls the latitude, related to the rotation of the Earth, with this controller we have the photovoltaic cell oriented in latitude in orthogonal position to the radiation of the Sun, see Fig. 5.



(a) (b)

Fig. 4. (a) Input/output variable membership functions and (b) input/output relationship; for control of rotation Motor1

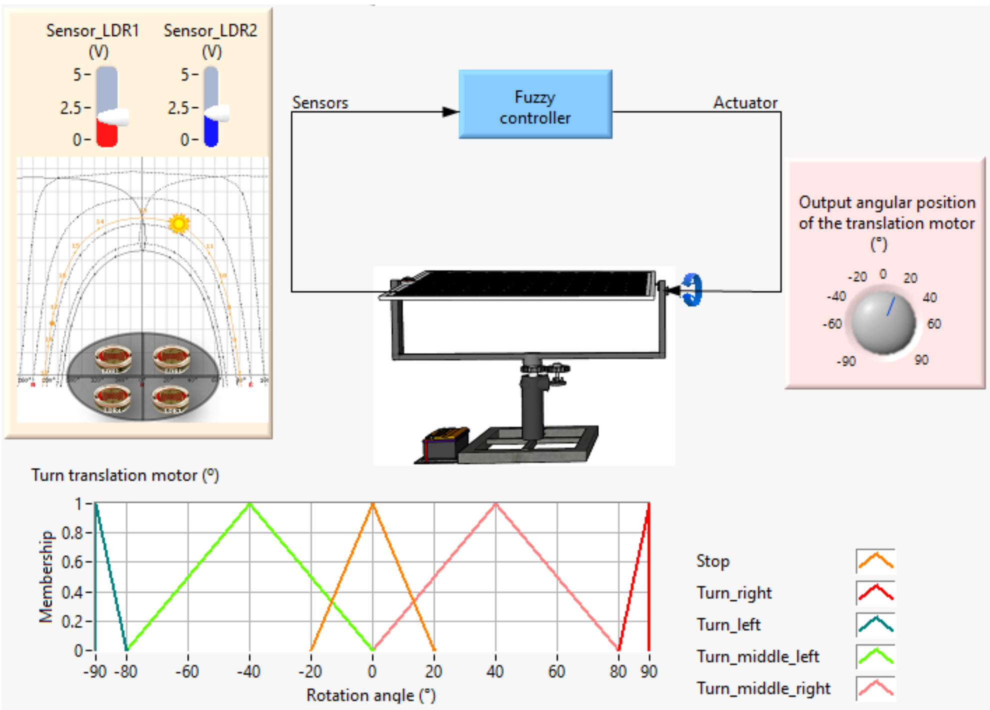
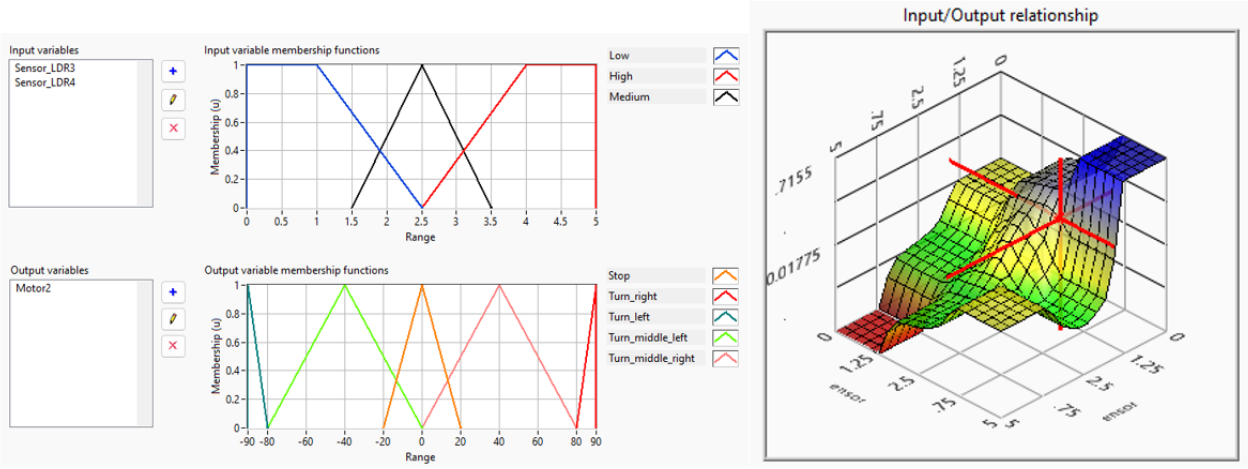


Fig. 5. Interface of the response of Motor1 related to the rotation of the Earth

The fuzzy longitude controller for the east-west rotation of the solar PV panel is designed using also the Mamdani type controller, considering the east-west Sun position as two inputs, the inference engine has also 09 rules detailed below:

1. *IF 'Sensor_LDR3' IS 'Low' AND 'Sensor_LDR4' IS 'Low' THEN 'Motor2' IS 'Stop'*
2. *IF 'Sensor_LDR3' IS 'Low' AND 'Sensor_LDR4' IS 'Medium' THEN 'Motor2' IS 'Turn_middle_right'*
3. *IF 'Sensor_LDR3' IS 'Low' AND 'Sensor_LDR4' IS 'High' THEN 'Motor2' IS 'Turn_right'*
4. *IF 'Sensor_LDR3' IS 'Medium' AND 'Sensor_LDR4' IS 'Low' THEN 'Motor2' IS 'Turn_middle_left'*
5. *IF 'Sensor_LDR3' IS 'Medium' AND 'Sensor_LDR4' IS 'Medium' THEN 'Motor2' IS 'Stop'*
6. *IF 'Sensor_LDR3' IS 'Medium' AND 'Sensor_LDR4' IS 'High' THEN 'Motor2' IS 'Turn_middle_left'*
7. *IF 'Sensor_LDR3' IS 'High' AND 'Sensor_LDR4' IS 'Low' THEN 'Motor2' IS 'Turn_left'*
8. *IF 'Sensor_LDR3' IS 'High' AND 'Sensor_LDR4' IS 'Medium' THEN 'Motor2' IS 'Turn_middle_left'*
9. *IF 'Sensor_LDR3' IS 'High' AND 'Sensor_LDR4' IS 'High' THEN 'Motor2' IS 'Stop'*

As a response to these rules implemented in Fig. 6 (a) we have the input/output variable membership functions, and in Fig. 6 (b) input/output relationship; for the control of the translation Motor2, which was also implemented with the fuzzy system designer tool of LabVIEW. The movement generated is related to the Earth's translation, with this controller the solar photovoltaic panel is oriented in length to maintain an orthogonal position to the Sun's radiation, see Fig. 7.



(a) (b)

Fig. 6. (a) Input/output variable membership functions, (b) input/output relationship for translation Motor2 control.

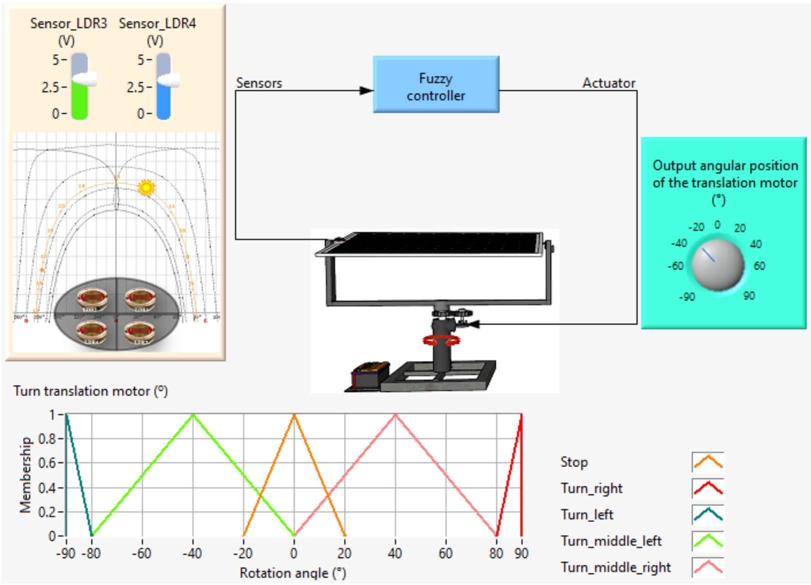


Fig. 7. Interface of the response of Motor2 related to the translation of the Earth.

The parameters measured to determine the improvement of electric power generation were the Ip and V_p generated by an artificial resistive load R_L of 10 Ω, with which the P_p was calculated. The measurements and storage of the sample data of these parameters were carried out automatically every 20 minutes starting at 6:00 am and ending around 6:00 pm, from the interface developed in LabVIEW. Of the photovoltaic panels used, one was fixed position located with an azimuth of –23.45° with respect to south and elevation of 12.39°, which is the best position for fixed solar panels; while the other photovoltaic panel was rotated in latitude and longitude according to data obtained by the fuzzy tracker.

IV. Results and Discussions

A. Results

The measurements of the electrical parameters in the PV panel with diffuse solar tracker: voltage in panel with solar tracker (V_{pft}), current in panel with solar tracker (I_{pft}), power in panel with solar tracker (V_{pft}); in the fixed position PV panel (azimuth: –23.45°, elevation: 12.39°): voltage in fixed position panel (V_{pfp}), current in fixed position panel (I_{pfp}) and power in fixed position panel (V_{pfp}). Shown in Table I is the data obtained in clear day that were obtained and recorded in an excel sheet automatically from the LabVIEW platform interface. The efficiency of the mobile PV panel improved by 25.28% with respect to the fixed PV panel.

Table I: Electrical Parameters Measured in the Photovoltaic Panel with Diffuse Solar Tracker and Fixed Position Photovoltaic Panel on Clear Day

Sample number	Sampling time	Photovoltaic panel with diffuse solar tracker	Photovoltaic panel with fixed position Azimuth: −23.45° Elevation: 12.39°
		P_{pft} (W)	P_{pfp} (W)
00	6:03:53	6.50	0.20
01	6:23:53	11.86	0.97
02	6:43:53	10.66	0.72
03	7:03:53	20.00	5.00
04	7:23:53	39.20	8.45

05	7:43:53	40.33	11.86
06	8:03:53	45.00	20.00
07	8:23:53	45.60	22.05
08	8:43:53	46.82	30.26
09	9:03:53	46.21	25.99
10	9:23:53	45.60	29.77
11	9:43:53	46.82	39.20
12	10:03:53	48.67	39.20
13	10:23:53	48.67	46.21
14	10:43:53	48.67	45.00
15	11:03:53	49.30	45.00
16	11:23:53	49.30	45.60
17	11:43:53	49.30	49.93
18	12:03:53	49.30	48.05
19	12:23:53	49.93	48.05
20	12:43:53	48.67	49.30
21	13:03:53	48.67	49.30
22	13:23:53	48.67	48.05
23	13:43:53	49.30	48.05
24	14:03:53	49.30	45.00
25	14:23:53	49.30	44.40
26	14:43:53	45.00	38.09
27	15:03:53	45.00	37.54
28	15:23:53	45.60	37.54
29	15:43:53	46.82	38.09
30	16:03:53	43.81	24.64
31	16:23:53	42.63	25.09
32	16:43:53	33.28	23.76
33	17:03:53	28.80	15.49
34	17:23:53	27.38	11.55
35	17:43:53	16.93	6.50
36	17:53:53	10.95	0.29

Data were taken on cloudy day and the results are presented in Table II, which were also obtained and recorded in an Excel sheet automatically from the LabVIEW platform interface. The efficiency of the mobile PV panel improved by 9.97% with respect to the fixed PV panel.

TABLE II: ELECTRICAL PARAMETERS MEASURED IN THE PHOTOVOLTAIC PANEL WITH DIFFUSE SOLAR TRACKER AND FIXED POSITION PHOTOVOLTAIC PANEL ON CLOUDY DAY

Sample number	Sampling time	Photovoltaic panel with diffuse solar tracker	Photovoltaic panel with fixed position Azimuth: -23.45° Elevation: 12.39°
		P_{pft} (W)	P_{pfp} (W)
00	06:08:00	3.04	0.12
01	06:28:00	6.06	0.57
02	06:48:00	5.07	0.43
03	07:08:00	9.94	2.96
04	07:28:00	18.12	5.01
05	07:48:00	18.35	7.03
06	08:08:00	21.68	11.86
07	08:28:00	22.97	13.07
08	08:48:00	24.61	17.94
09	09:08:00	22.32	15.41
10	09:28:00	20.75	17.65
11	09:48:00	22.61	23.24
12	10:08:00	22.50	23.24
13	10:28:00	25.94	27.40
14	10:48:00	24.16	26.68
15	11:08:00	24.11	26.68
16	11:28:00	23.81	27.04
17	11:48:00	25.20	29.60
18	12:08:00	22.43	28.49
19	12:28:00	23.69	28.49
20	12:48:00	24.54	29.23
21	13:08:00	25.58	29.23
22	13:28:00	24.88	28.49
23	13:48:00	23.13	28.49
24	14:08:00	23.07	26.68
25	14:28:00	23.81	26.33
26	14:48:00	22.68	22.58
27	15:08:00	22.05	22.26
28	15:28:00	22.97	22.26
29	15:48:00	21.96	22.58
30	16:08:00	21.43	14.61
31	16:28:00	19.40	14.87
32	16:48:00	16.06	14.09
33	17:08:00	13.51	9.18
34	17:28:00	13.22	6.85
35	17:48:00	8.18	3.85
36	18:08:00	5.36	0.17

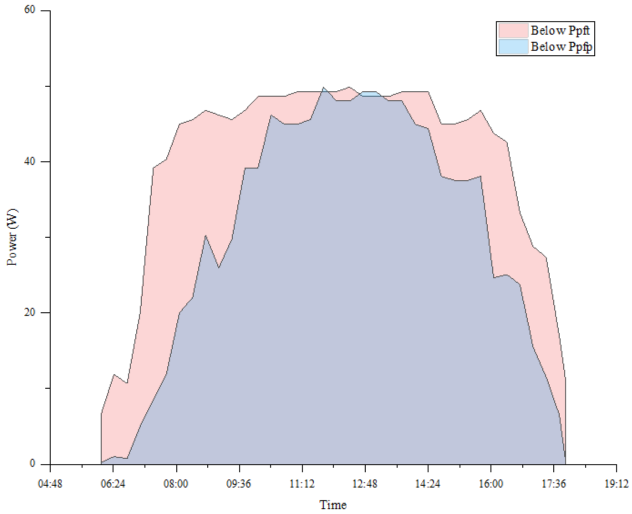


Fig. 8. Solar efficiency ratio between PV panel with solar tracker (P_{pft}) and fixed position PV (P_{pfp}) on a clear day.

B. Discussions

From the results, on clear or sunny days the PV panel with diffuse solar tracker presented a higher solar efficiency in the morning before 11:30 hours and in the afternoon after 14:00 hours approximately, with respect to the fixed position PV panel which is presented in Fig. 8, where the power of both PV panels generates energy of similar dimensions from 12:00 to 13:30 hours. The total efficiency during the day represents an improvement in electricity generation of about 25.28%.

While in cloudy days the PV panel with diffuse solar tracker presented a slightly higher efficiency during the morning before 11:30 hours and in the afternoon after 14:00 hours approximately, with respect to the fixed position PV panel which is presented in Fig. 9, the power generated by the fixed position PV panel was higher from 10:00 to 16:00 hours, this was due to the cloudiness during the day due to the dispersion of solar radiation, because the LDR sensors detected the same irradiance in the schedule where the fixed position PV generated higher power. The total efficiency during the cloudy day represented only about 8.97% improvement in electric power generation.

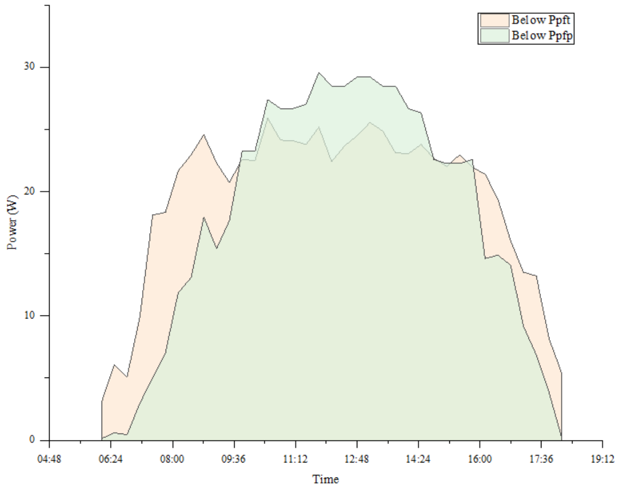


Fig. 9. Solar efficiency ratio between PV panel with solar tracker (P_{pft}) and fixed position PV (P_{pfp}) on a cloudy day.

When determining the energy produced by the PV panel with solar tracker based on fuzzy logic with respect to the energy produced by the PV panel with fixed position presented in Fig. 8 and Fig. 9; the photovoltaic and current generation increased in spite of the cloudy day, having a performance. These results are related to the various works related to solar trackers with feedback, mainly constituted by LDR sensors.

V. Conclusion

This paper presents the implementation of a solar tracker based on fuzzy control on which a PV panel was mounted, being the sensors an LDR array with semicircular blades that allowed to keep the PV panel in orthogonal position to the solar radiation. The solar tracking mechanism was implemented using fuzzy logic control using nine rules for the control of each DC motor, these rules were implemented in the fuzzy system designer tool of LabVIEW which allowed the rotation of the motors from −90° to 90° the driver circuit of the DC motors were controlled by the PIC 18F4550 microcontroller. A comparative analysis was performed to evaluate the energy efficiency of the PV panel with solar tracker based on fuzzy control, with respect to a fixed position PV panel with azimuth of –23.45° with respect to the south and elevation of 12.39° because it is close to the equator. From the experimental results, the efficiency of the PV panel with fuzzy control, based tracker with proposed LDR sensors was higher in the clear or sunny day reaching 25.28%; and while in the cloudy day it was observed that the energy obtained is lower 8.97%, in both cases without considering the operational energy consumption.

The application of this type of mechanisms can be generalized to different solar panels that require to be optimized in the capture of solar energy. For future research, it is recommended to embed the fuzzy logic algorithm in microcontrollers to reduce costs.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

H. Carbajal-Morán and C. A. Galván-Maldonado conducted the research, with implementation of the solar tracker, data analysis and validation of results; J. F. Márquez-Camarena contributed to the editing of the article/figures; all authors approved the final version.

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Hipólito Carbajal-Morán received the first degree in electronic engineering from the National University of Huancavelica, Peru, in 2006; obtained the Mg. degree in systems engineering from the National University of Central Peru, in 2011; has the Ph.D. degree in environmental sciences and sustainable development from the National University of Central Peru, in 2021. He is currently a professor in the Electronics Department, Faculty of Electronics-Systems Engineering, National University of Huancavelica, Peru. His field of research includes automation, artificial intelligence and energy management.

Javier F. Márquez-Camarena received the first degree in systems engineering from the National University of Central Peru, Peru, in 2001; obtained the master degree in administration from the National University of Central Peru, in 2006; has the Ph.D. degree in systems engineering from the National University Federico Villarreal, Peru, in 2021. He is currently a professor in the electronics department of the Faculty of Electronics-Systems Engineering at the National University of Huancavelica, Peru. His field of research includes automation.

Carlos A. Galván-Maldonado received the first degree in electronic engineering from the National University of Engineering, Peru, in 1999. He is currently a professor in the electronics department of the Faculty of Electronics-Systems Engineering at the National University of Huancavelica, Peru. His field of research includes automation and advanced control.