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ADVANCE DESIGN OF DUAL AXIS SOLAR TRACKING SYSTEM USING FUZZY LOGIC

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Abstract— The demand for solar-generated power has surged in recent years due to the adverse environmental effects associated with fossil fuel usage, which have led to the proliferation of dangerous diseases. The efficiency of solar systems in generating power is heavily dependent on solar radiation intensity. Consequently, the primary challenge in improving solar systems lies in achieving high efficiency during daylight hours. This paper introduces a novel dual-axis solar tracker mechanism designed to optimize the capture of solar radiation by solar panels, regardless of weather conditions. The proposed solar tracking system employs fuzzy logic control

Energy Generation, Efficiency Improvement

to track the sun's position at any given time. By calculating the sun's relative position using Earth's angles, the system provides the necessary instructions to adjust the stepper motor, accordingly, thereby tracking the movement of the sun and maximizing light radiation. MATLAB Simulink was employed to simulate the proposed approach, and the results demonstrate superior energy production compared to a fixed system. The proposed solar tracking system achieves a power output of 10141.220 kW/m² with an accuracy of approximately 6%, surpassing the fixed system's output of 9920.346 kW/m². Experimental tests were conducted using a solar panel and the dual-axis solar tracker to evaluate the system's performance. The solar tracker was programmed to accurately follow the sun's path throughout the day, and measurements were taken at various times. The experimental results indicate that the proposed solar tracking system outperforms a fixed system even under cloudy conditions, offering enhanced energy generation and improved overall efficiency for solar systems. Thus, the dual-axis solar tracker presented in this study represents an effective mechanism for enhancing the efficiency of solar systems.

I. Introduction

Renewable energy sources such as solar energy, wind energy, and geothermal have been rapidly used in electric power generation. Solar energy is the most popular and reliable type of renewable source because it directly converts the received energy into electric power [1]. The conversion process from light intensity to current is often accomplished by using solar cells, electronic devices invented in 1957 [2]. A group of solar cells connected forms a Photovoltaic module (PV). The optimized method for improving the performance of solar cells is by developing new methods to increase the received light intensity [3]. A Solar tracker is an electronic system used to keep solar panels in the sun's position, representing the best solution for improving the output power of the solar system [4]. The purpose of solar trackers is to maintain the operating solar panel at the knee point of the power-volt characteristics, providing the maximum output power [5]. Solar trackers can be classified into two types based on their free axes: single-axis solar trackers and dual-axis solar trackers. The performance of solar trackers depends on the type of controller, which can be an intelligent system such as a fuzzy controller or a conventional system such as a PID controller [6]. The fuzzy controller provides ease of use and does not require a complex mathematical model.

The proposed paper's advanced mechanism contributes to reducing the need for fuels in generating electric power by improving the efficiency of solar systems. There are many published papers in the field of designing solar trackers but most of these systems were based on tracking the sun’s position by sensing the light intensity. In this paper, fuzzy logic was used to optimize the performance of a dual-axis solar tracking system based on the sun-earth geometrical relationship, thus it does not affect by external weather factors such as clouds and rain. The paper proposes a control strategy that combines the inputs from a variety of sensors, including altitude angle, hour angle, and declination angle to determine the optimal angle for the solar panels. By using fuzzy logic to process these inputs, the system can make more accurate and timely adjustments to maximize the energy output of the solar panels. The contributions of this paper are significant in several ways. Firstly, the use of fuzzy logic allows for more precise and efficient control of the solar tracking system, which can increase the energy output of the solar panels. Secondly, the proposed system is designed to be cost-effective and easy to implement, which makes it suitable for use in both residential and commercial settings. Lastly, this research provides a valuable contribution to the field of renewable energy by demonstrating the potential of fuzzy logic as a tool for optimizing the performance of solar tracking systems.

II. Literature Review

Most of the related studies in this field were common in designing solar tracking systems, but they were some differences in terms of control strategy or the sensing tools of the sun position for instance Mustafa [7] explained a simple design of a solar tracker system based on Light Dependent Resistors (LDR) sensor, the system contains two motors, but it did not include an intelligent control method such as fuzzy logic. Mousavi et al [8] also presented calculations for a solar tracker based on a sun-earth geometrical relationship without showing hardware or using an intelligent control method such as fuzzy. Akbar et al [9] illustrated a dual axes tracking system based on an LDR sensor and used by an AVR microcontroller; the system provides higher efficiency compared with a fixed axes system. Sinha [10] showed a simulation design of dual axes sun tracker which used a PID controller to control the motor speed; the detecting element was an LDR sensor, and the structure was composed of four LDRs. Similarly, Zakariah et al [11] presented dual axes sun tracking design using four LDR sensors based on the fuzzy logic method. Pradeep et al [12] illustrate the real-time design of a sun tracking system simulated by using Lab View and the main control element was Arduino

Uno; as most of the previously published structures, it used four LDRs sensors to track the sun position at any time. A design based on the programmable logic controller (PLC) of the sun’s tracking system was introduced in Mahmood [13]; the system used sun angles equations for tracking the sun's positions, but it did not have any support from any intelligent control method. Merve [17] conducted an evaluation in Trabzon, one of the provinces in Turkey known for its cloudy weather. The research aimed to determine the optimal motor steps for a two-axis solar tracking system. This system was designed to ensure that solar rays would reach a perpendicular angle (90°) to the system, utilizing an open-loop control system. The solar tracking system was developed based on the sun's angle of incidence, controlled by a microcontroller. The results showed that the designed solar tracking system is approximately 24.7% more efficient compared to the fixed system. Fatima [18] In order to maximize the utilization of solar energy under various weather conditions, the author developed an automatic solar tracker controlled by a microcontroller. This design incorporates mathematical models and sensors to accurately determine the position of the sun. The solar tracker system includes light-dependent resistors (LDRs), an Arduino microcontroller with Wi-Fi connectivity, a servo motor, a current sensor, and a solar panel supported by a metallic servo bracket. This electromechanical system is equipped with a driver and a servo motor for rotation, resulting in enhanced collection efficiency compared to a stationary device. Nurzhigit [19] The objective of the study was to create an efficient single-axis solar tracker capable of accurately following the sun's trajectory in different weather conditions. To accomplish this, the researchers suggested implementing a schedule and light-dependent resistor (LDR) photosensors in the single-axis solar tracker. Through simulations and experiments, the performance of the proposed solar tracker was evaluated. A comparison was made between its energy output and that of a fixed-tilt solar panel system and a traditional single-axis solar tracker. The findings indicated improved results, particularly in cloudy and rainy weather conditions, making it suitable for the development of solar trackers in regions with diverse climates.

III. Solar Angles Equations

The basic structure of the proposed system is based on the calculations of the sun-earth angles which were used as input–output data to Fuzzy Logic. Four important angles govern the position of the sun and the solar panel:

- The Latitude angle φ which determined the location of either the south or north equator plane.
- Hour angle: this angle relates the rotation of the earth at any time and the solar noon, this angle is given by equation (1):

$$\omega = 15(Ts - 12)) \qquad (1)$$

where:
ω= Hour angle in degrees
Ts= Local solar time

- The declination angle measured the declination in degrees of the sphere on the equatorial plane. It calculated by equation (2):

$$\delta = 23.45\, sin \left[360\left(\frac{284+n}{365}\right)\right] \qquad (2)$$

where:
δ=Declination angle in degrees
n= The days number for month

- Zenith angle defines the angle between the sun's position and the vertical line on the surface of the earth, this angle is given by equation (3):

$$\theta z = sin\,\delta\, sin\,\varphi + cos\,\delta\, cos\,\varphi\, cos\,\omega \qquad (3)$$

where:
δ= Declination angle in degrees
θz= Zenith angle

IV. Methodology

The flow chart shown in Figure 1 describes the operating steps in each interval, starting with the inputs to the fuzzy set-based classifier, namely latitude, hour angle, and zenith angle, which are given to the fuzzy inference system through the fuzzification block. The fuzzy inference block is the heart of the system as it processes the input data and gives the zenith angle as the output. The inference system accomplishes the task of forecasting by using the fuzzy rule base prepared by the forecaster. The accuracy of the forecast depends on the experience of the forecaster, the rules prepared by the forecaster, and the number of rules prepared. After the inference system gives the output, the defuzzification block converts the fuzzified output into a crisp output, which can be further displayed on a graph known as the load curve. Firstly, the historical data is examined, and the maximum and minimum ranges of different parameters are obtained. These ranges are used in the process of fuzzifying different parameters, such as latitude angle and hour angle. After the fuzzification is done, forecasting rules are prepared based on the different parameters of the angle. These rules are the heart of the fuzzy system, so utmost care should be taken in preparing them. Once the rules are prepared for the desired hour, the output obtained is compared with the actual zenith angle, and the error in zenith angle load forecasting is used to improve the rule base for future forecasts, as shown in Figure 1.

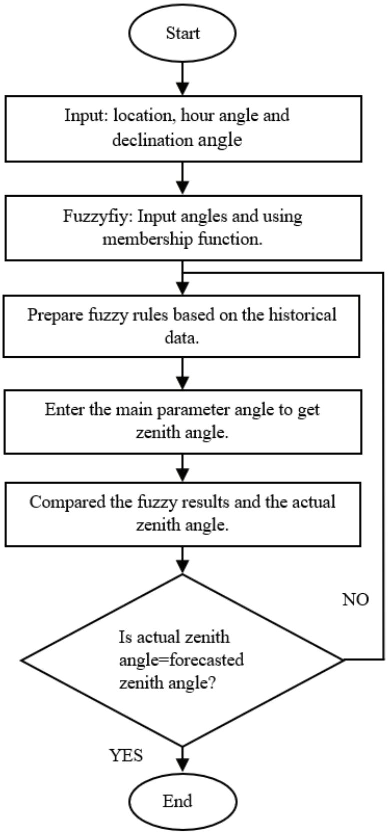
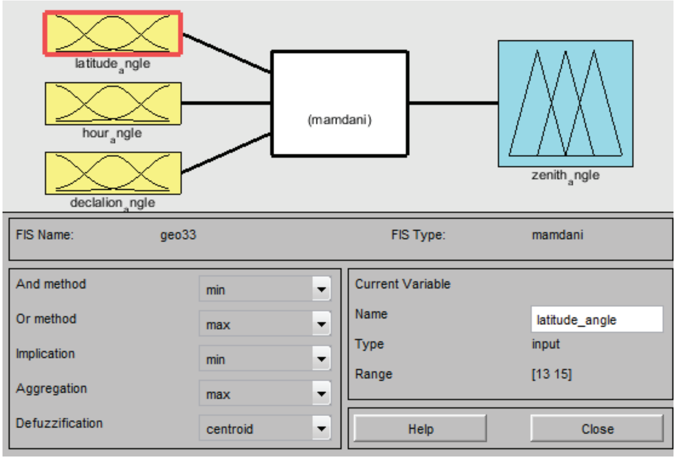


Figure 1: Flow chart

V. Modeling of Fuzzy Logic Controller

Mamdani's approach was used to implement FLC for the sun tracker. FLC contains three basic parts: Fuzzification, Base rule, and Defuzzification. Figure 2 shows the whole structure of the fuzzy logic system including input, reasoning rules, and also the proposed output. The inference rules relate the input to the output and every rule represents a fuzzy relation.



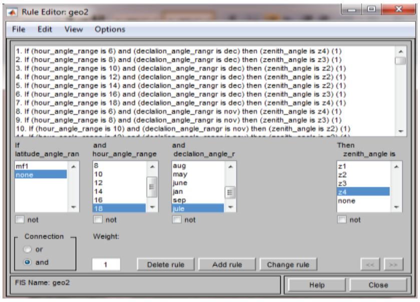
FIS Name: geo33
FIS Type: mamdani
And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid
Current Variable
Name: latitude_angle
Type: input
Range: [13 15]

Figure 2: Fuzzy model

The knowledge of defining the fuzzy rules for the desired relationship between input variables (hour_angle_range and declination_angle_range) and output variables "zenith_angle." Each rule consists of an "if" part (antecedent) and a "then" part (consequent). in terms of the membership functions illustrated in the control rules as shown in Figure 3 the fuzzy rules evaluated by an inference mechanism. In this study, the 84 fuzzy rules provided defines the mapping between the input variables (hour_angle_range and declalion_angle_range) and the output variable (zenith_angle) based on the given membership functions. The rules cover various combinations of input conditions and assign corresponding output values as a set of the following formula:

1. If (hour_angle_range is 6) and (declalion_angle_range is Dec) then (zenith_angle is z4)
2. If (hour_angle_range is 8) and declination_angle_range is Dec) then (zenith_angle is z3)
3. If (hour_angle_range is 10) and declination_angle_range is Dec) then (zenith_angle is z2)
4. If (hour_angle_range is 12) and declination_angle_range is Dec) then (zenith_angle is z2)
5. If (hour_angle_range is 14) and declination_angle_range is Dec) then (zenith_angle is z2)
6. If (hour_angle_range is 16) and declination_angle_range is Dec) then (zenith_angle is z3)
7. If (hour_angle_range is 18) and declination_angle_range is Jule) then (zenith_angle is z4)

The input hour angle of the proposed fuzzy model is divided into a set of ranges as specified in Table 1.



1. If (hour_angle_range is 6) and (declalion_angle_rangr is dec) then (zenith_angle is z4) (1)
2. If (hour_angle_range is 8) and (declalion_angle_rangr is dec) then (zenith_angle is z3) (1)
3. If (hour_angle_range is 10) and (declalion_angle_rangr is dec) then (zenith_angle is z2) (1)
4. If (hour_angle_range is 12) and (declalion_angle_rangr is dec) then (zenith_angle is z2) (1)
5. If (hour_angle_range is 14) and (declalion_angle_rangr is dec) then (zenith_angle is z2) (1)
6. If (hour_angle_range is 16) and (declalion_angle_rangr is dec) then (zenith_angle is z3) (1)
7. If (hour_angle_range is 18) and (declalion_angle_rangr is dec) then (zenith_angle is z4) (1)
8. If (hour_angle_range is 6) and (declalion_angle_rangr is nov) then (zenith_angle is z4) (1)
9. If (hour_angle_range is 8) and (declalion_angle_rangr is nov) then (zenith_angle is z3) (1)
10. If (hour_angle_range is 10) and (declalion_angle_rangr is nov) then (zenith_angle is z2) (1)

Figure 3: The fuzzy rules

Table 1: Fuzzy range of hour angle

Variable	Crisp input range	
6	-9	-75
8	-75	-45
10	-45	-15
12	-15	15
14	15	45
16	45	75
18	75	90

Table 2: Fuzzy range of hour angle

Variable	Crisp input range	
Jan	17	-23
Feb	17	-8
March	-8	-4
Apr	4	15
May	15	22
Jun	22	23
July	23	18
Aug	18	8
Sep	8	-4
Oct	-4	-15
Nov	-15	-22
Dec	-22	-23

Similarly, the input fuzzy logic of the declination angle was specified into different ranges as shown in Table 2.

VI. Simulink Model

Figure 4 illustrates the Simulink block diagram for the Fuzzy controller for the sun tracker system. As shown in Figure 4, four inputs (day, month, latitude angle, and hour angle) were applied to the model to control the stepper motor directly to the correct sun position. The stepper provides a motor good choice in controlling the rotation of the angle due to its excellent response and the proportional relation between the rotation angle and the input control pulse.

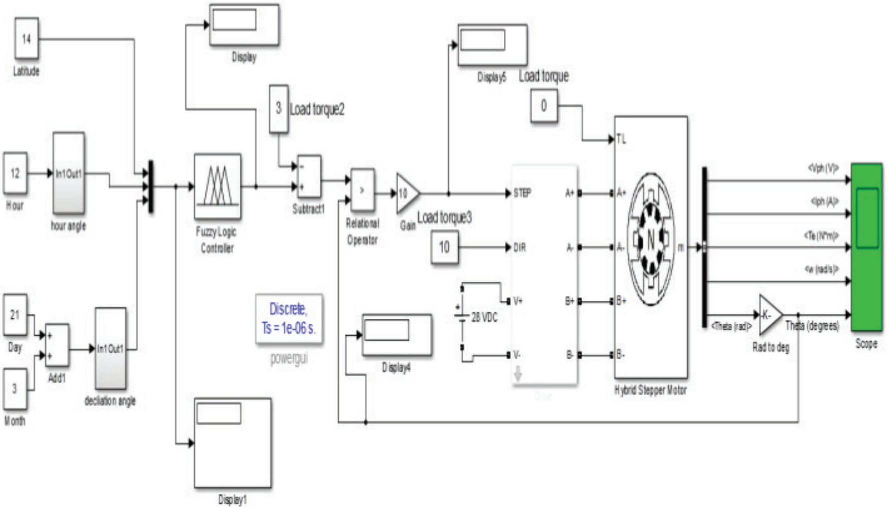


Figure 4: Simulink Model

VII. Results and Discussions

The experimental data of the zenith angle were calculated as shown in Table 4 the obtained results were distributed for different months in wad Medani city in Sudan by calculating the hour angle and declination angle for the same in each hour and calculating the range value for all months. The hour angle via fuzzy logic controller has negative values in the morning and positive values in the afternoon time, the higher value during the morning was + 90 degrees and the lowest during the afternoon was - 90 degrees.

Table 4: Zenith angle

Month	Hour Angle (Degrees)		Declination Angle (Degrees)		Output Zenith Angle (Degrees)	
Jan	90	-90	-17	-23	30.5	93
Feb	90	-90	-17	-8	30	90
March	90	-90	-8	-4	11.2	90.8
Apr	90	-90	4	15	7	88
May	90	-90	15	22	7	90
Jun	90	-90	22	23	7	90
July	90	-90	23	18	7	90
Aug	90	-90	18	8	7	86
Sep	90	-90	8	-4	7	90
Oct	90	-90	-4	-15	20.2	90.9
Nov	90	-90	-15	-22	30.5	95
Dec	90	-90	-22	-23	30.5	93

The results of the zenith angle were calculated based on the fuzzy controller. Then it was compared with the conventional calculation method of the zenith angle for other months during the year. The maximum fuzzy forecast zenith angle results compared with the actual calculated results as shown in Figure 5.

The higher zenith angle for the proposed sun tracking system calculation by the fuzzy logic controller was 93 degrees whereas the actual zenith angle for the calculation was 95 degrees. Similarly, the minimum fuzzy forecast zenith angle results compared with the actual minimum calculated zenith angle results were shown in Figure 6.

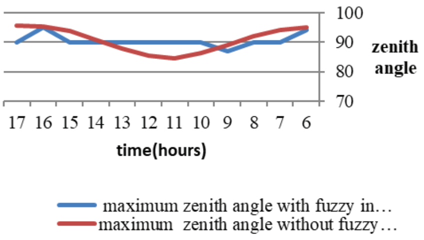


Figure 5: Maximum zenith angle

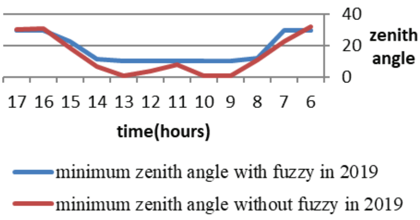


Figure 6: Minimum zenith angle

The results of the proposed system based on a fuzzy controller were close to the actual maximum zenith angle and minimum zenith angle. The error ratio of the zenith angle obtained by Fuzzy is calculated for the day of 21st March 2019 using equation (4).

$$\%Error = \frac{actual\ zenith\ angle - Fuzzy\ zenith\ angle}{actual\ zenith\ angle} \times 100 \qquad (4)$$

The obtained results for the day 21^{st} March 2019 were plotted in the curve shown in Figure 7. From the curve it was observed that the fuzzy zenith angle curve was almost compatible with the actual.

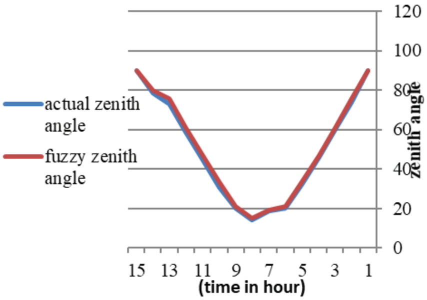


Figure 7: Zenith angle curve of 21^{st} March 2019

The error ratio of the zenith angle which was calculated on the day 21^{st} March 2019 shows a less error ratio of 0.01% and a large error ratio of 6%. Similarly, the obtained results for the day 21^{st} of December 2019 were plotted in the curve shown in Figure 8.

As shown from the curve; it was observed that the fuzzy zenith angle curve was almost compatible with the actual. The smallest error ratio was 0.8% and the largest ratio was 6%.

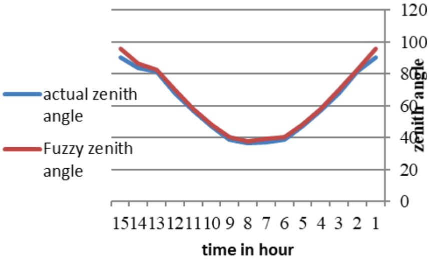


Figure 8: Zenith angle curve of 21st December 2019

VIII. Output power

The output energy (W/m^2) of dual axis solar photovoltaic panel for 21^{st} March 2019. Calculate from the equations sequentially,

$$P_{OUT} = H \times \sin(\alpha + \beta) \qquad (5)$$

where:

H = direct beam

β = angle between the module and the horizon

α = Elevation angle

By calculating the total energy for the proposed system based on fuzzy controller, it was found that the total output energy was 10141.220 kW/m^2 where the actual total output energy was 9920.346 kW/m^2 for 12 hours (from 6:00 am to 18:00 pm) with the enhancement of 520.874 kW/m^2. By comparing the results of the proposed paper with some related papers, it showed that the obtained power in Dola [10] is 0.9926 kW/m^2 and Hao [16] 11.59455 kW/m^2, while the obtained power in the proposed system is given power bout 10141.22 kW/m^2.

IX. Conclusion

In this study, a sun tracking system was developed to increase the amount of power generated by the solar panel as the sun travels across the sky. Fuzzy logic is used to control the movement of the solar panel based on geometrical angles of the sun. The obtained power output of 10141.220 kW/m^2 further validates the effectiveness of the system. This study shows that it is possible to significantly increase the amount of power generated by solar panels using altitude angle, hour angle, and declination angle as inputs and by formulating rules based on fuzzy logic using available data. One of the advantages of using fuzzy logic in this system is that it allows for accurate prediction of the zenith angle, which is used to determine the position of the sun. The study found that the fuzzy logic approach was able to predict the zenith angle with a high degree of accuracy, with an error rate of approximately 6%. This suggests that the use of fuzzy logic could lead to increased efficiency in solar panel systems, resulting in higher power output and increased cost-effectiveness. Additionally, the use of geometrical angles of the sun in the sun tracking system makes it more resistant to environmental factors such as cloud cover and shading, which can often interfere with the accuracy of traditional systems that use LDRs. This means that the developed system could be more reliable and effective in a wider range of environmental conditions. The findings of this study are significant for the renewable energy industry. The use of fuzzy logic in sun tracking systems could improve the efficiency and reliability of solar panel systems, helping to increase the adoption of renewable energy sources and reduce dependence on fossil fuels. Furthermore, the obtained power output of 10141.220 kW/m^2 demonstrates the practical application and potential benefits of the developed sun tracking system on fossil fuels.

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