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Abstract

Purpose: To investigate how the number of rules in the fuzzy controller affects the single-axis solar tracking system's orientation accuracy.

Methodology: Design and compare FLC49 and FLC25 controllers, each with different organic rules and functions. To improve the system efficiency by accurately measuring the maximum power point, the controller receives comparison results from the light sensors installed on the solar panels. We study and analyze the controllers, selecting the best one based on the accuracy of the solar panel orientation. Using the FLC output to operate a two-phase SM.

Findings: This study developed a sun tracking system using Matlab/Simulink and compared FLC49 and FLC25 controllers. FLC49 performed better in simulations, with lower settling time and overshoot. The number of rules significantly influenced accuracy, and it also showed lower transient ripple magnitudes, accelerating time response.

Unique Contribution to Theory, Practice and Policy: The research investigates the effectiveness of rules in a fuzzy controller and recommends the optimal number of windings to achieve precision in controlling a stepper motor. The study explores the use of 49-rule and 25-rule fuzzy logic controllers to control a stepper motor based on LDR sensor inputs. The researchers found that while both controllers had similar steady time error and overshoot, they differed in orientation accuracy, with the 49-roll fuzzy controller being more accurate in orientation. This single-axis solar tracking system optimizes solar energy conversion into electricity.

Keywords: *Membership Functions, Fuzzy Logic Control, Stepper Motor, Solar System*

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INTRODUCTION

Globally, the amount of electrical energy used is always increasing. Burning fossil fuels or nuclear processes generate and utilize the majority of the electrical energy. Thermal and nuclear power plants contribute to environmental pollution, while alternative energy sources like solar, geothermal, wind, wave, bioenergy, and hydrogen are eco-friendly.

Solar energy is a particularly significant source of energy. Solar energy has the capacity to significantly contribute to meeting the majority of the world's heating, cooling, and electrical demands while simultaneously having the ability to address our environmental challenges. Sunlight, an infinite and clean energy source, provides 10K times the Earth's energy needs. Solar energy has gained popularity in the previous two decades. Solar energy conversion and energy generation are essential for the planet's growth and development [1].

The sun's daily and yearly variations in radiation pose a serious challenge to solar energy. The availability of sunlight limits the use of solar energy, leading to intermittent consumption. Therefore, the impracticality of solar energy, stemming from its high cost and suboptimal efficiency, limits its use. In order to address these issues, several academics have conducted studies on efficient and practical approaches to harnessing solar energy [2]. The solar tracking system is one of the techniques employed. This method entails adjusting the solar panel's orientation based on the location of the sunlight throughout the day. Therefore, researchers develop solar tracking systems (STS) in various ways to maximize the use of solar radiation. Solar tracking systems may enhance energy production efficiency by up to 35% on an annual basis. Compared to permanent systems, STSs are more efficient, especially in the winter when seasonal fluctuations take place.

Numerous studies on control techniques have been carried out by researchers to satisfy the needs of different systems, including STSs. Specifically, one of these research has focused on fuzzy logic-based control systems. Instead of relying on the presence of a mathematical model, we can develop a control method based on fuzzy logic by using the collected knowledge about the system's behavior [3]. In other words, by using fuzzy logic and cluster operations, robots may simulate human decision-making. The fuzzy logic approach lowers costs, expedites application, and enhances system performance. This situation greatly maximizes the system's performance, which enhances control efficacy and responsiveness. AL-Rousan N. et al. (2020) study presents two intelligent solar tracking control systems using the Adaptive Neural Fuzzy Inference System (ANFIS) concept. The systems aim to enhance the performance of solar trackers by accurately predicting the sun's trajectory and minimizing errors. They train and test the controllers using experimental data, concentrating on tilt and orientation angles. The models show high prediction rates and low error rates, achieving optimal performance for both single and dual-axis STS's [4].

Conversely, the neural network concept is non-linear model that is user-friendly, comprehensible, non-parametric, and extensively used in comparison to other models. Nevertheless, the neural network concept functions as a black-box modeling and learning strategy, specifically designed for circumstances where certainty is required. However, it is unable to elucidate the intricate link between input and output variables in complicated scenarios [5] [6]. This study presents the design of a fuzzy logic control system to accomplish the desired tracking. We also integrate the conventional control system into the system and scrutinize both control systems' performances. We conducted the simulation using the Matlab/Simulink program, specially designed for dynamic system simulation.

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Problem Statement

To produce the maximum possible energy from solar panels, the angle between the sun's rays and the panel's surface must be a right angle, which is not possible in the case of a fixed solar energy production system. Therefore, we must design an efficient controller to align the solar panel's angle with the sun's rays throughout the day. Use fuzzy theory to create a controller that adjusts the solar panel's inclination angle to maximize its energy output throughout the day. Using fuzzy theory to create a controller that adjusts the solar panel's inclination angle to maximize its energy output throughout the day.

METHODOLOGY

Position solar panels perpendicular to the sun's direction for maximum efficiency, particularly in areas with intense lighting. Nevertheless, an efficient solar tracking system can optimize the use of solar panels due to the varying direction of sunlight throughout the day and different seasons. Single directional light-detecting circuit, one amplifier to power the motor, and one stepper motor (SM) drives make up this system. The system's operational power consumption may be decreased, efficiency increased, and total energy generating capacity enhanced with this approach [7]- [10].

The sunlight incidence angle detection circuit consists of two LDR sensors, mounted on the solar panel and placed inside a container. the two sensors set up so that LDR1 and LDR2 follow the sun's horizontal rays [8]. If one solar panel receives more light than the other, it indicates a misalignment and generates an erroneous voltage. In order to get the panel perfectly perpendicular to the light source's beam, an amplifier circuit takes the error voltage and utilizes it as a command to run the motor. The diagram illustrates a control system for solar tracking in a single direction. The horizontal control architecture is seen in Fig. 1.

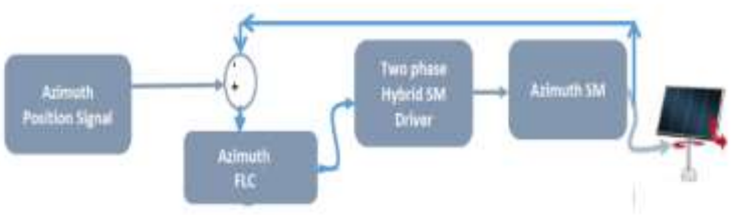

Figure 1: A fuzzy logic controller-based single-axis solar tracking system block diagram.

Stepper Motor Model

There are two common varieties of SM: variable-reluctance and permanent-magnet or hybrid SM. The mechanical and electrical parts of a stepper motor work together. The electrical sector is defined by a similar circuit, the exact layout of which is motor-specific. The underlying assumption of the analog circuits is that the magnetic circuit is linear, saturation-free, and that the mutual inductance between phases may be ignored. The mechanical section's state-space model is defined by the inertia moment and the viscous friction coefficient. In Figure 2, shows the one-phase analog circuit of a variable-reluctance SM motor.

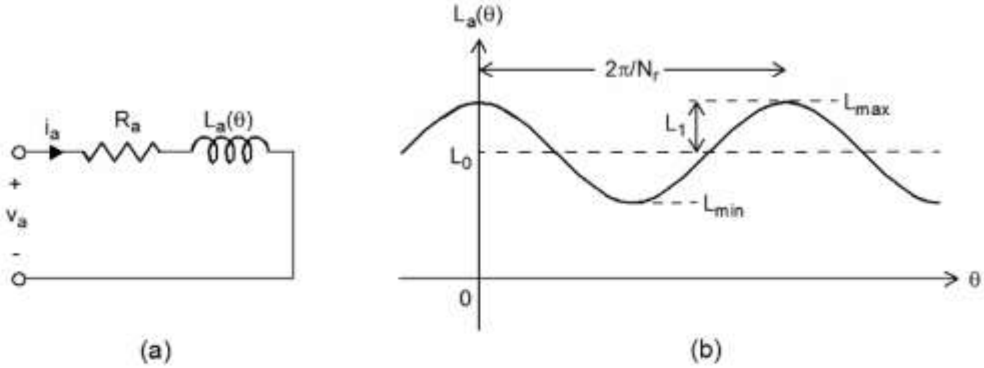

Figure 2. Hybrid SM motor equivalent circuit.

The phase A winding's resistance (*Ra*) and inductance (*La*(*θ*)) are denoted in this model, respectively. Based on the rotor's position, the inductance of the winding varies, as seen in Eq. 1.

$$L_a(\theta) = L_0 + L_1 \cos (N_r\theta) \qquad (1)$$

L_1 stands for the maximum inductance variation, whereas L_0 stands for the average inductance. The rotor's tooth count is denoted by Nr. The maximum A-phase winding inductance may be achieved when the rotor tooth is at its reference position ($\theta = 0$), which is in perfect alignment with the A-axis pole. The total electromagnetic torque that a motor produces is equal to the sum of the torques that are generated by each phase of the motor (Eq. 2).

$$T_e = \sum_{x=1}^{m} 0.5 i_x^2 \frac{dL_x}{d\theta} \qquad (2)$$

In this Eq. 2, "i_x" stands for the current flowing through the winding in phase "*x*" and "*m*" for the number of stages. For any given phase *x*, the inductance of the winding is represented by the function L_x. The north pole of the rotor must be perfectly aligned with the A-axis pole at the reference point ($\theta = 0$) for the A-phase to generate a back electromotive force (EMF) value of zero. Eq. 4 shows that the phase currents, magnetic fluxes, and detent torque from the rotor's saliency combine to produce electromagnetic torque in a two-phase PM or hybrid stepper motor.

$$T_e = -p\psi_m i_a \sin(p\theta) - p\psi_m i_b \sin(p\theta - \pi/2) - T_{dm} \sin(mNr\theta) \qquad (4)$$

given that m is the number of phases of the motor, where m is equal to 2. The formula for the rotor's tooth count is Nr = 2*p, where p is an integer.

Design and Analysis of a Fuzzy Controller

A powerful tool for developing state-of-the-art control systems. The use of fuzzy logic has become more common. With the help of fuzzy logic, even the most complex requirements may be met by means of inexpensive, easily manufactured controllers. The variety and amount of applications using fuzzy logic has grown substantially in the last few years. The consumer electronics, industrial process control, medical equipment, and decision support system domains are only a few examples of the many possible uses. Numerical understanding is inadequate for many decision-making and problem-solving tasks. Nevertheless, individuals achieve success by relying on imperfect information rather than accurate knowledge. The principle of system accuracy ratio serves as the foundation for fuzzy logic. Fuzzy logic control has shown to be more effective than traditional control methods in several simulations and experiments. Consequently, FLC has become a popular option for regulating electrical motor drives with extensive parameter fluctuation in the realm of industrial electronics. Still, changing a number of factors, such as input and output gains, control rules, and membership functions, makes building and fine-tuning FLC controllers a difficult procedure. Fuzzy logic controllers (FLCs) may be designed more efficiently by extracting application-specific values from the parameters of derived models [11][12].

Critical to the operation of any conventional control system is its design, which is usually grounded in the mathematical model of the plant. using a precise mathematical model and known parameters, we may construct a controller for targeted performances by analyzing it using Bode or Nyquist plots. Nevertheless, these processes take a lot of time. In addition, FLC can adapt to systems with unknown parameter fluctuations and load disturbances, allowing it to achieve resilient performance. Membership functions are used in fuzzy logic to determine the extent to which words in a collection of linguistic variables have precise physical meanings.

The controller design is derived from the comparison findings of light sensors (LDR) installed on the solar panel. Its purpose is to optimize the system's efficiency by accurately measuring the maximum power point. Each azimuth corresponds to a two-input-one-output configuration. The FLC was specifically built for the current use. The inputs to the FLC consist of incorrect values. The error e(k) is defined as the difference between the set-point position and the measured position, as well as the change in error. The formula for calculating the current error, ce(k), is obtained by subtracting the prior error from the present error. Two FLC controller with different rules number are designed and comparted. FLC49, which had 49 rules, and FLC25, which had 25 rules, were subsequently renamed. Two inputs are defined inside a discourse universe that has seven membership functions (negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM), and positive big (PB)) for FLC49 and (negative big (NB), negative small (NS), zero (ZE), positive small (PS), positive big (PB)) for FLC25, respectively, for each proposal controller. This results in a grand total of 49 rules, 25 of which are specific to each azimuth. To operate the two-phase SM, the FLC (CU) output is used as an input. The following defines the FLC's inputs and controlled output:

$$e(d)= x(d) - y(d) = E \quad (5)$$

$$ce(d)= e(d) - e(d-1) = CE \quad (6)$$

$$CU = cu(d) \quad (7)$$

The steps used to create the FLC model in the Matlab/Simulink environment are detailed in the section that follows. In order to represent effectively, fuzzy logic controllers rely on fuzzy membership functions. Membership functions of the triangle and trapezoid shape find widespread usage. This approach employs the triangle membership function for both the fuzzification and defuzzification stages [13].

Matlab R2017a is used to build the solar tracking system's Simulink Fuzzy Logic Controller. In Figure 3, it is observed. There are six stages to the design process of the simulation.

The input stage determines the fuzzy controller's input variables. Azimuth is the adjusted value for the input parameters. The processing stage determines the feedback signal for the real location, pairs it with the system's set points, and provides the error and error-rate linguistic variables. The fuzzy controller will then use these variables as input. The FLC's purpose is to adjust the solar panel's orientation to a 90-degree angle in relation to the sun's beams by regulating the panel's azimuth. The FLC produces a duty cycle output ranging from 0% to 100% for an aid device that is coupled to two-phase stepper motor driver blocks. In order to control the stepper motors, the system first obtains the outputs. The main goal of the system is to coordinate the input position profile with the speed of the solar tracking stepper motor. The system does this by maintaining a constant rate of acceleration up to the target speed, and subsequently a constant rate of deceleration down to a stop. Due to its ability to accurately position the solar panel in relation to the sun, the linear velocity profile provides a clear benefit in such situations.

To activate the stage, you need a regulated voltage source and a control mechanism that uses a bridge configuration of no more than four power switches to provide one stepper motor with power. A regulated voltage source is activated by the fuzzy output signal, which in turn transforms the input signal into a voltage source of the same value. Power electronic devices with four power switches might be either forced-commutated devices (such as IGBTs and MOSFETs) or naturally commutated devices (such as diodes or thyristors). The inverter generates a square voltage by use of pulse width modulation (PWM). At the plant stage, it acts like SM. This block takes the actuation step's outputs as inputs. We evaluate the solar tracking system's SM models and provide the processing step with position outputs as feedback. Use of monitoring oscilloscopes and LCD probing are part of the monitoring and probing processes. These tools allow us to precisely assess the system's health and make adjustments as needed. You may see the SM characteristics that were utilized for the simulation in Table 1.

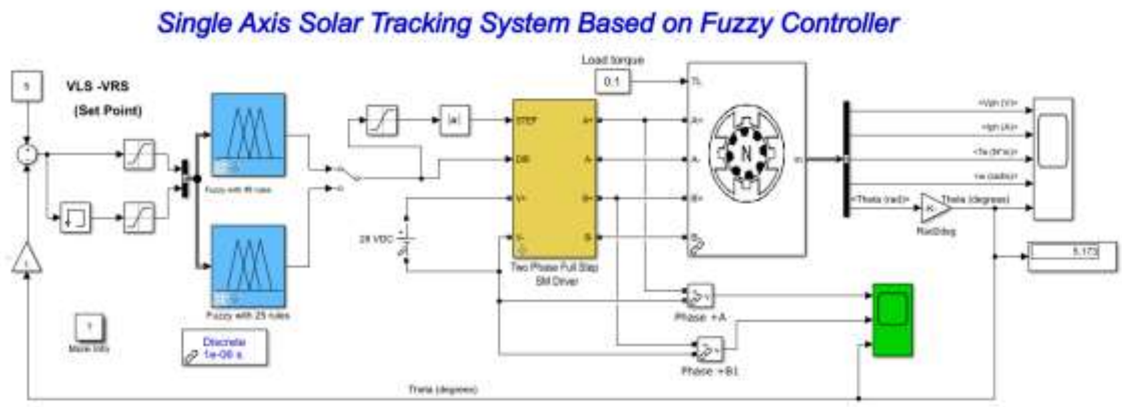

Figure 3: Shows The Solar Tracking System's Simulink Model

Table 1: Parameters of SM

Motor Type	Permanent Magnet Hybrid SM
Number of Phase	2
Winding Inductance	1.4e-3 H
Winding Resistance	0.7 Ω
Moment of inertia (J)	1.2e-7
Step Angle	1.8º
Initial Position	0 º

The flow chart in figure 4 illustrates the primary program of the tracking algorithm for the project's proposed tracking system. The structure chart and flowchart provide a valuable framework for the practical execution of the program's code.

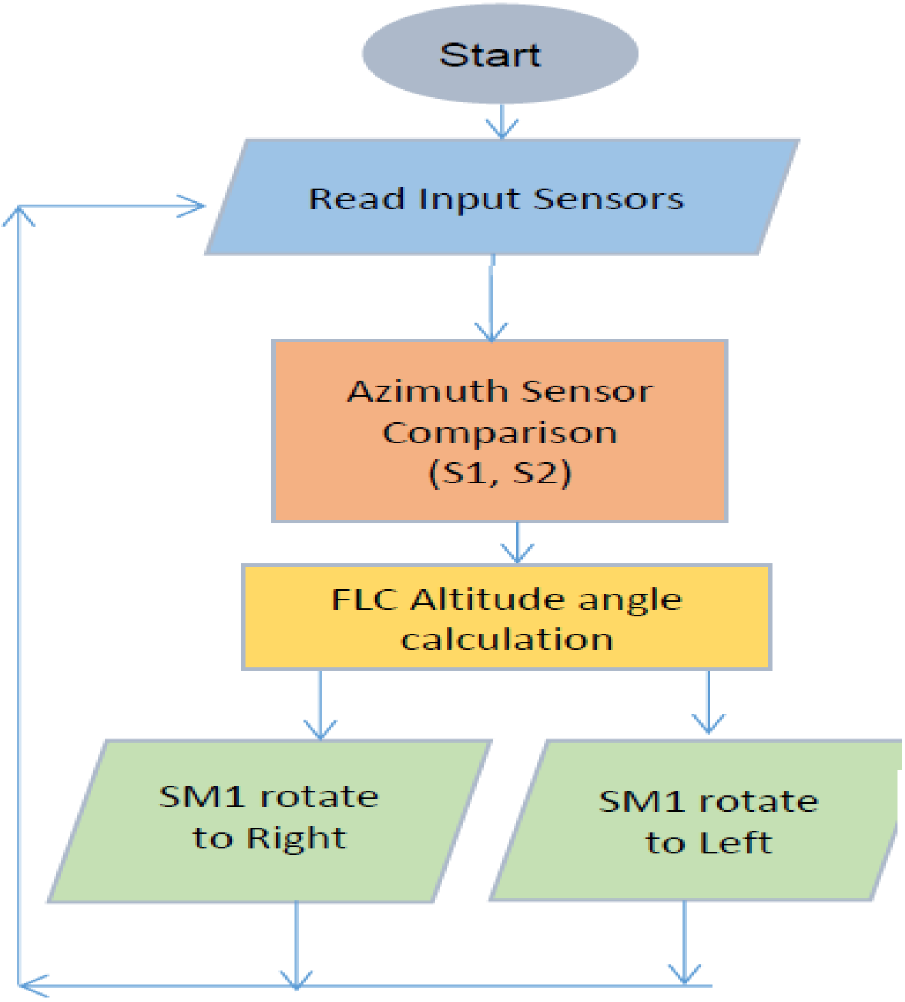

Figure 4. System Operation based on proposed algorithm.

RESULTS

For the sake of comparison and validation, the solar tracking system is simulated using both the FLC49 and FLC 25 controllers. As illustrated in Figure 1, the system's block diagram was created using Matlab/Simulink. You can see the outcomes of the simulation in the figures below. For a more precise comparison, the system responses from the FLC25 and FLC49 controllers are shown on the same graph for a specific angular position. Figure 5 shows the system output for the FLC25 and FLC49 controllers. When compared to the FLC25 controller, the FLC49 shows a faster response time and fewer overshooting.

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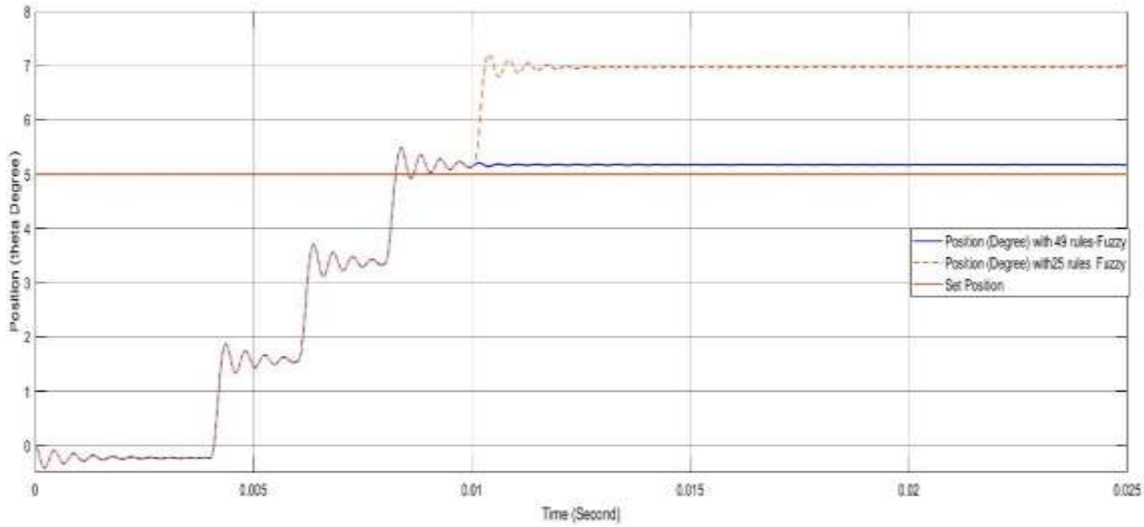

Figure 5. The Position Output of FLC49 and FLC25 Controllers

The FLC controller's fixed reference input inaccuracy drops to zero after a short while. The system responses from the FLC25 and FLC49 controllers, as applied to the system at different angles, are shown in Figure 6.

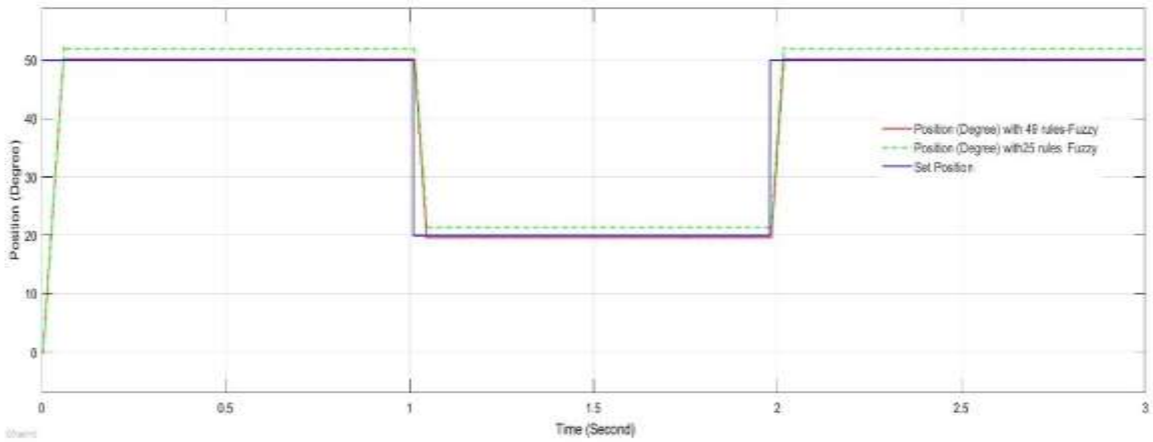

Figure 6. The Variable Angular Position Outputs of the System from both FLC49 and FLC25 Controllers

While there are variations in position during the initial period, both controllers track changes in the reference input. The response time of both FLC49 and FLC25 controllers are same when there are sudden changes in the reference position input. When the load on the motor shaft is changed from 0.1N to 0.4N, Figure 7 shows how the FLC49 and FLC25 controllers react to the varied reference input.

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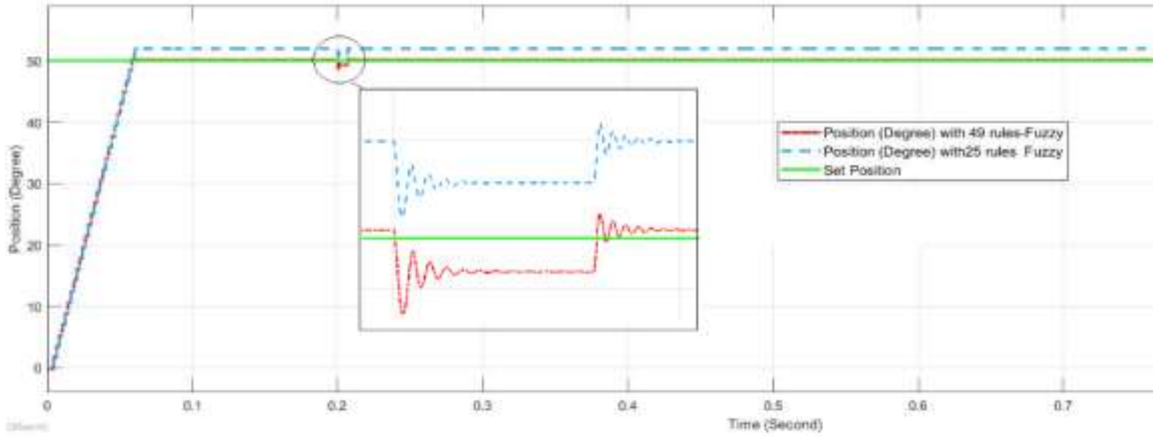

Figure 7: Shows the FLC49 and FLC25 System Positions as the Load Changes from (0.1-0.4)N.

Figure 7 shows that both controllers exhibit the same degree of overshoot and steady-state error, but FLC49 is more accurate when applying a load to the motor shaft. The system's inaccuracy grows in proportion to the increasing load on the motor shaft. Figure 8 shows how the FLC49 controller's inaccurate variable load input varies with time.

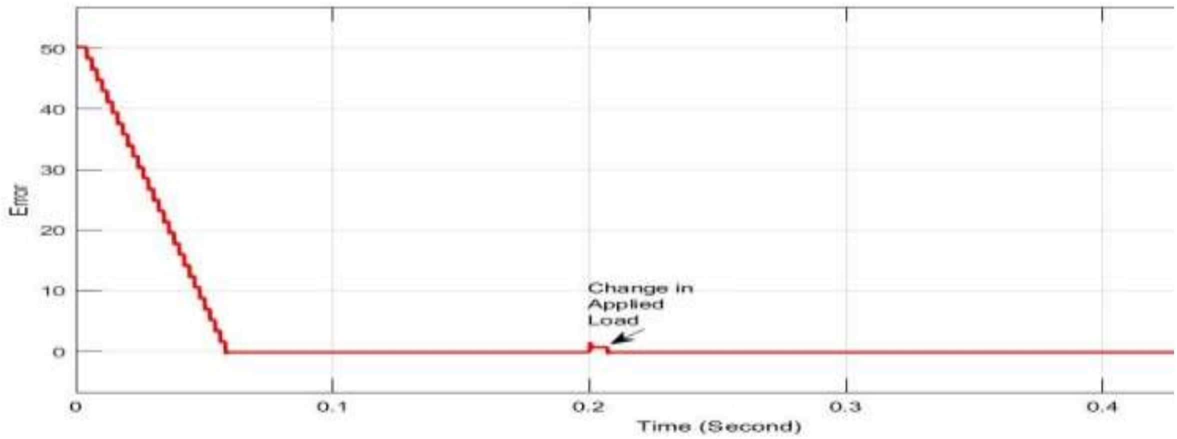

Figure 8. Variable load error changes for FLC49 controller

Still, during the transients, the present reactions of the controllers are different. When utilizing FLC49 as a controller, the current ripples less during transients than when using FLC25.

CONCLUSION

Using the Matlab/Simulink environment, this study developed a sun tracking system and suggested a way to operate it. A comparison is made between the outcomes produced by the FLC49 and FLC25 controllers and the planned FLC with 49 regulations. When compared to FLC25, the FLC49 performed better in the simulations. The settling time and overshoot of FLC49 and FLC25 are almost identical, however FLC49 demonstrates better accuracy. Research shows that the number of rules is significant in defining the controller's accuracy, which is the most important benefit of this suggested control. It also exhibits lower transient

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ripple magnitudes. The use of such a controller speeds up the time response, according to findings gained in practice.

The study examines the effectiveness of fuzzy controller rules in controlling a stepper motor using 49-rule and 25-rule controllers. Results show 49-roll controllers are more accurate in orientation, enhancing solar energy conversion into electricity.

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