OPTIMIZING SOLAR ENERGY WITH SMART CONTROL: A COMPARATIVE STUDY OF FIXED, FUZZY, AND ANFIS SYSTEMS

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Abstract
Solar energy has emerged as a cornerstone of renewable energy, with the potential to address critical energy challenges, especially in developing nations like Nigeria. The efficiency of photovoltaic (PV) systems hinges significantly on the orientation of solar panels to maximize solar irradiance capture. This paper explores advanced solar tracking technologies, focusing on the comparative performance of fixed-axis, fuzzy logic, and Adaptive Neural-Fuzzy Inference System (ANFIS) controllers. Through rigorous modeling and simulation using MATLAB/Simulink, the study examines key performance parameters such as rise time, settling time, peak response, and steady-state error under varying solar conditions. The findings reveal that while fuzzy logic controllers provide a significant improvement over fixed-axis systems, ANFIS controllers outperform both, achieving superior tracking precision, reduced energy loss, and enhanced power output. These advancements underscore the transformative potential of intelligent solar tracking systems in optimizing renewable energy utilization. The results validate the effectiveness of intelligent controllers in improving energy capture and set the stage for further innovation in solar technology to meet global energy demands sustainably.

Keywords: *Fuzzy logic controller, ANFIS controller, MATLAB, Simulink*

1. Introduction

Solar energy is rapidly gaining popularity as an important means of expanding renewable energy resources. As such, those in engineering fields must understand the technologies associated with this area. In some developed countries, such as

Britain, France, etc., renewable energy solutions are becoming increasingly important and popular (Joseph, 1991). Hence, if deployed in developing countries like Nigeria, where interrupted power supply is the order of the day, resulting in a very high cost of living, the story of poor supply of electricity in this country will change for the better (Ahmed, 2009). Since the beginning of mankind, energy from the sun has been used to dry clothes and food. Still, it was not until 1839 that a French physicist named Edmund Becquerel realized that the sun's energy could produce a "photovoltaic effect" (photo means light and voltaic means electrical potential). In the 1880s, selenium photovoltaic (PV) cells were developed that could convert sunlight into electricity (Merigan, 1975). Photovoltaic cells are specialized semiconductor diodes that convert sunlight directly into electricity. They are made of semiconducting materials similar to those used in computer chips. When sunlight is absorbed by these materials, the solar energy liberates electrons from their atoms and allows the electrons to flow through the materials to produce electricity (Morega & Bejan, 2005). The photovoltaic (PV) effect was proposed by Albert Einstein in the early 1900s, for which he won a Nobel Prize (Latha et al., 2019).

The three major sources of renewable energy are hydro, wind, and solar. Solar energy is the fastest-growing source of renewable energy. In 2021, solar energy generation saw a record 22% increment globally (estimated at 172 terawatt-hours). It accounted for 3.6% of global energy generation. One reason for its growth is the ease of deployment when combined with hydro and wind turbines. Those in engineering fields must understand the technologies associated with this area. In some developed countries, such as Britain, France, etc., renewable energy solutions are becoming increasingly important and popular (Joseph, 1991). Hence, if employed in developing countries like Nigeria, where interrupted power supply is the order of the day, resulting in a very high cost of living, the story of poor supply of electricity in this country will change for the better (Ahmed, 2009).

Maximizing power output from a solar system is desirable to increase efficiency. To maximize power output from the solar panels, the panels need to be aligned with the sun as the sun moves from east to west across the horizon. As such, a means of tracking the sun is required (Abah & Ochagwuba, 2001). This is a far more cost-effective solution than purchasing additional solar panels. It has been estimated that the yield from solar panels can be increased by 30 to 40 percent by utilizing a tracking system instead of a stationary or fixed array (Han, 2008). A solar tracking system allows more energy to be produced because the solar array can remain aligned with the sun. By generating electricity through the sun, one prevents the release into the atmosphere of around 500 tons of greenhouse gases each year (Merigan, 1975). Trackers direct solar panels or modules toward the sun. These devices change their orientation throughout the day to follow the sun's path to maximize energy capture (Basore, 2006).

2. Literature Review

This section reviews existing research on solar tracking and control systems, highlighting key advancements in design and performance.
Servo motor-based controllers have shown significant improvements in solar panel alignment. Ahmed (2009) introduced an intelligent controller for solar tracking, which greatly enhanced sun alignment over fixed panels. Similarly, Prodhan et al. (2016) developed a microcontroller-based single-axis tracker, achieving a 15% increase in solar energy capture compared to static systems.

Fuzzy logic has been widely explored for dual-axis tracking systems. Bandiyah et al. (2012) compared linear regression and fuzzy logic approaches, with fuzzy logic achieving a 30.5% power increase compared to linear regression's 29.3%. Using fuzzy logic for sensorless tracking controllers, Bandiyah et al. (2012) demonstrated a 20.2% boost in power output for dual-axis PV systems. In Kushal et al., (2021), the world economies are starting to move towards solutions that address both the global energy dilemma and the mounting evidence of climate change. One of the most well-known and widely used renewable energy sources to date is solar electricity. This study illustrates the performance advantages of a dual-axis solar tracker in contrast to other photovoltaic systems. A dual axis solar tracker can simultaneously measure the sun's radiation in the horizontal and vertical axis. For maximum effectiveness, the gadget monitors both daily tilt and seasonal variations. The study focuses on the design and development of an autonomous dual axis solar tracker prototype using Arduino code written for microcontrollers, as well as the fundamental properties of solar panels and their applications.

According to Ali et al., (2021), the performance of various maximum power point tracking techniques for Photovoltaic (PV) systems has been presented, under uniform and non-uniform irradiance conditions. Under uniform irradiance conditions, the power voltage curve of PV systems is nonlinear and contains one peak point whose location appertains to the irradiation and surface temperature of the PV system. Partial shading on PV modules reduces the generated power than the maximum power generated from each module separately. In Musa et al., (2023), although photovoltaic (PV) panels are extensively used to convert solar energy into electric energy, the continuous change in the sun's angle with reference to the earth's surface limits their capacity to collect sufficient energy. To improve efficiency, solar trackers are used to constantly adjust the PV panels towards the sun to maximize energy capture.

Arduino-based solar trackers have been frequently utilized due to their cost-effectiveness and versatility. Nurhani et al. (2020) designed an automatic dual-axis solar tracker system using Arduino and light-dependent resistors (LDRs), achieving higher voltage and current outputs than fixed systems. Aniruddho et al. (2019) also developed a cost-effective dual-axis tracker controlled by Arduino, notable for its movement flexibility despite its higher cost compared to single-axis models. Bandijah et al. (2021) introduced a sensorless fuzzy logic-based tracking system, showcasing its capability to achieve accurate panel orientation while minimizing reliance on extensive sensor data, thereby simplifying the system and lowering costs.

Katkade (2021) designed an intelligent solar tracking system employing fuzzy logic and servo motors, emphasizing the benefits of linguistic control rules over traditional algorithms, particularly in adapting to rapidly changing solar conditions. Astronomical tracking methods have been employed to optimize panel positioning. Elkhadiri et al. (2018) used astronomical algorithms combined with smart relays to adjust panel angles based on lunar calendar positions, showing superior performance over static systems.

PID controllers have been applied for solar tracking, emphasizing alignment accuracy. Chan et al. (2020) implemented a PID-controlled system using Ziegler-Nichols tuning, which improved tracking precision but experienced high overshoot and prolonged settling times.

Ndinechi et al. (2009) and Boumaaraf et al. (2016) classified trackers as passive, active, or manual and as single or dual-axis systems. Joseph (1991) conducted a comparative analysis of single and dual-axis configurations, finding nearly equal emphasis in publications on both types. These studies collectively demonstrate the advancements in solar tracking technologies, highlighting their potential to enhance energy efficiency and sustainability. However, these existing designs and implementation of smart solar tracker systems did not make use of the combination of Fuzzy logic controller and ANFIS controller for improved performance. This paper seeks to address the identified research gaps.

3. Methods

3.1 Modeling of PV Array System

Photovoltaic solar power is one of the most promising renewable energy sources in the world. At noon on a cloudless day at the equator, the power of the sun is about 1 kW/m², as the sun rays come perpendicular to a plane. PV arrays can track the sun throughout each day to greatly enhance energy collection. A remote home can be virtually self-sufficient with solar power. A solar tracker orients a solar photovoltaic panel or concentrating solar reflector, or lens, towards the sun to maximize irradiation. The sun's position in the sky varies both with the seasons and time of day as the sun moves across the sky. The solar energy intercepted by the solar panels during the day is not maximized if the position of the panel is always static. Dynamically oriented solar panels can track the sun throughout each day to greatly enhance energy collection. The required accuracy of the solar tracker depends on the application. Concentrators, especially in solar cell applications, require a high degree of accuracy to ensure that the concentrated sunlight is directed precisely to the powered device. Typically, concentrator systems will not work at all without tracking. Considering a PV solar cell shown in Figure 1, the equivalent circuit, which mathematically describes the I-V characteristics of the PV circuit, is represented in Equation 3.1.

$$\boldsymbol{I = I_{ph} - I_o\left[exp\left(\frac{V+R_sI}{CV_ba}\right) - 1\right] - \frac{V+R_sI}{R_p}} \tag{3.1}$$

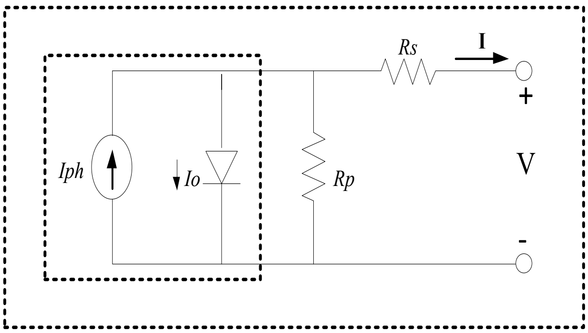

Figure 1: Single diode model circuit

Where $\boldsymbol{R_s}$ is the series resistance, $\boldsymbol{R_p}$ is the resistance in parallel $\boldsymbol{a}$ is the diode ideality constant, $\boldsymbol{V_b}$ is the thermal voltage of the solar cell, $\boldsymbol{I_o}$ is the diode saturation current, and $\boldsymbol{R_{ph}}$ is the photovoltaic (light-generated) current.

Diode ideality factor is the measure of how much a practical diode deviates from the ideal diode equation. The average value assumed during the determination of unknown parameters in the photovoltaic system is usually 1.3. Also, the thermal voltage is a characteristic voltage that relates current flow in the p-n junction to the electrostatic potential across it, and is given as

$$\boldsymbol{V_b = \frac{kT_n}{q}} \tag{3.2}$$

Where $\boldsymbol{k}$ is Boltzmann constant ($\mathbf{1.3806503 \times 10^{-23}}$ J/K), $\boldsymbol{q}$ is electron charge ($\mathbf{1.607 \times 10^{-19}}$ $\boldsymbol{C}$), and $\boldsymbol{T_n}$ is nominal temperature ($\mathbf{298.15K}$).
The light-generated current of the photovoltaic cell depends linearly on the solar irradiation and is also influenced by the temperature, and their relationship is given in Equation 3.3

$$\boldsymbol{I_{ph} = \left(I_{phn} + K_{cu}\Delta_T\right)\left(\frac{G}{G_n}\right)} \tag{3.3}$$

$\boldsymbol{I_{phn}}$, light generated current in the solar cell circuit at nominal conditions (when temperature is 25 °C and irradiance of 1000 W/m^2), $\boldsymbol{K_{cu}}$ is the current temperature coefficient, $\Delta_T = \boldsymbol{T - T_n}$, $\boldsymbol{T}$ is the actual temperature and $\boldsymbol{T_n}$ is the nominal temperature, $\boldsymbol{G}$ is the actual sun irradiation and $\boldsymbol{G_n}$ is the nominal sun irradiation (usually 1000 W/m^2). The diode saturation current $\boldsymbol{I_o}$ and its dependence on the temperature may be expressed as

$$\boldsymbol{I_o = I_{on}\left(\frac{T_n}{T}\right)^3 exp\left[\frac{qE_g}{ak}\left(\frac{1}{T} - \frac{1}{Tn}\right)\right]} \tag{3.4}$$

Where, $\boldsymbol{E_g}$ is band gap energy of a semiconductor $\boldsymbol{E_g = 1.12}$ **eV** for the polycrystalline Si at 25 °C.
Where $\boldsymbol{I_{on}}$ is given by the relationship in Equation 3.4

$$\boldsymbol{I_{on} = \frac{I_{sc}}{exp\left(\frac{V_{oc}}{CaV_b}\right) - 1}} \tag{3.5}$$

And $\boldsymbol{I_{sc}}$ is the short-circuit current, and $\boldsymbol{V_{oc}}$ open circuit voltage, respectively.

3.2. Modeling of Solar Tracking Angles

The position of the sun during any time of day is calculated by knowing the azimuth and elevation angles. Both the azimuth angle ∅, and elevation angle $\boldsymbol{\beta}$ measured from any point on the earth's surface.

The elevation angle $\boldsymbol{\beta}$ is the angle between the sun rays and the horizontal surface (solar panel).

$$\boldsymbol{\sin\beta = \sin\delta\sin L + \cos\delta\cos L\cos\varepsilon} \tag{3.6}$$

It is complementary to the zenith angle $\boldsymbol{\theta_z}$

$$\boldsymbol{\theta_z = 90^0 - \beta} \tag{3.7}$$

where $\boldsymbol{L}$ the latitude angle of the location is, $\boldsymbol{\delta}$ is the declination angle, and $\boldsymbol{\varepsilon}$ is the hour angle.
The accuracy of the declination angles is important in navigation and astronomy. However, an approximation accurate to within 1 degree is adequate in many solar purposes. One such approximation for the declination angle is

$$\boldsymbol{\delta = \sin^{-1}\{0.39795\cos[0.98563(N - 173)]\}\ (degrees)} \tag{3.8}$$

where $\boldsymbol{N}$ is day number and calendar dates are expressed as the $\boldsymbol{N = 1}$, starting with January 1. Thus, March 22 would be $\boldsymbol{N = 31 + 28 + 22 = 81}$ and

December 31 means $\boldsymbol{N = 365}$. The hour angle, $\boldsymbol{\varepsilon}$ in degrees expresses the time of day concerning the solar noon. It is the angle between the planes of the meridian-containing observer and the meridian that touches the earth-sun line. It is zero at solar noon and increases by 15° every hour, and is represented as in Equation 3.9

$$\boldsymbol{\varepsilon = 15(t_s - 12)} \tag{3.9}$$

where $\boldsymbol{t_s}$ is the solar time in hours. A solar time is a 24-hour clock with 12:00 as the exact time when the sun is at the highest point in the sky. The concept of solar time is to predict the direction of the sun's rays relative to a point on the earth. Solar time is location or longitudinal dependent. It is generally different from local clock time (LCT) defined by political time zones.

For the horizontal coordinates, the azimuth angle $\emptyset$, is given as 0^0 in north direction, east $+90^0$, west $270^{0,}$ and south 180, shown in equation 3.10

$$\boldsymbol{\emptyset = 180^o + \cos^{-1}\left(\frac{\sin\beta\sin L - \sin\delta}{\cos\beta\cos L}\right)} \tag{3.10}$$

The azimuth angle for True Local Time <12.00hr is expressed as in Equation 3.11,

$$\boldsymbol{\emptyset = 180^o - \cos^{-1}\left(\frac{\sin\beta\sin L - \sin\delta}{\cos\beta\cos L}\right)} \tag{3.11}$$

Where $\boldsymbol{L}$ is the latitude of the location, $\boldsymbol{\beta}$ is the elevation angle and $\boldsymbol{\delta}$ is the declination angle.

The time of sunrise and sunset depends on the time of year and the latitude of any specified location on Earth. A trigonometric formula can be used to compute the time of sunrise and sunset, given as a function of the number of hours before and after the local noon. The term "local noon" means the time of day when the sun is directly overhead. Due to the effects of Daylight-Saving Time and asymmetric time zone boundaries, the local noon does not always correspond to 12:00 pm. The equation is represented in 3.12

$$\boldsymbol{H = \left|\frac{1}{15}\cos^{-1}\left[-\tan(L)\tan\left(23.44\sin\left(360\frac{(D+284)}{365}\right)\right)\right]\right|} \tag{3.12}$$

3.3 Fuzzy Membership Function

In a solar tracking system, the fuzzy logic membership function (figure 2) is essential for handling uncertainties and variability in inputs like solar angle and tracking error. Membership functions classify continuous inputs into fuzzy sets, such as "low," "medium," or "high," which enables flexible, human-like data interpretation. Unlike traditional binary logic, fuzzy logic allows partial membership, meaning an input can belong to multiple sets to different extents, with values between 0 and 1. For example, a solar angle may be categorized as partly “low” and “medium,” depending on the membership function's shape. Typically, triangular or bell-shaped membership functions are used to represent these transitions smoothly, based on parameters that define their range and slope. This setup allows the solar tracking system to make nuanced adjustments to panel positions, optimizing energy capture even under changing light conditions.

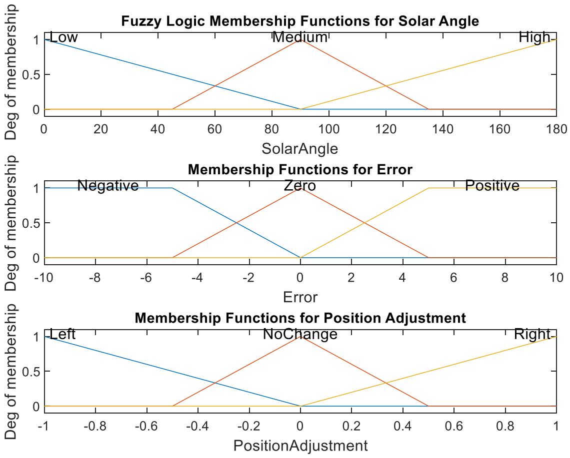

Figure 2: Fuzzy Membership Function

The Simulink diagram of a solar tracking system using a fuzzy logic controller shown in figure 3 provides a dynamic simulation environment to control the solar panels effectively. In this setup, the fuzzy logic controller adjusts the angle of the solar panels to ensure they are always aligned with the sun, maximizing energy capture. The key components in the Simulink model include inputs like solar radiation, the current angle of the sun, and the panel's position. These inputs are fed into the fuzzy logic controller, which uses predefined fuzzy sets and membership functions to interpret the data.

Within the fuzzy logic controller block, the error between the desired solar panel angle and the actual panel position is computed. The controller processes this error along with the rate of change to decide how much adjustment is needed. The membership functions (such as "low," "medium," and "high" for solar angle) allow the system to handle varying environmental conditions with flexibility. Fuzzy inference rules, stored in the controller, determine the output adjustments based on these inputs.

This output is sent to a motor or actuator block, which moves the solar panel to the optimal position. The Simulink model provides real-time simulation, showing how the fuzzy logic controller continuously adjusts the panel in response to changing sunlight conditions, improving efficiency and energy capture.

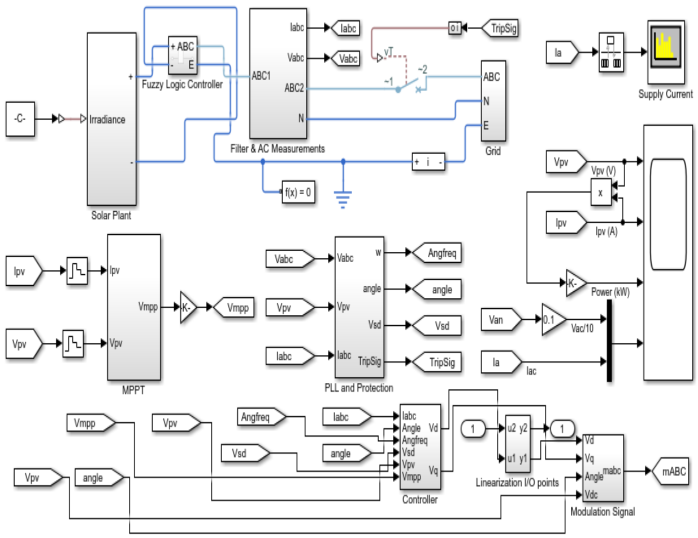

Figure 3: Fuzzy Logic Simulink Controller Model

3.4 Adaptive Neural Fuzzy Inference System Controller (ANFIS)

This section explained the ANFIS implementation in the solar system. ANFIS adjusts the membership function and related parameters to approach the required data sets using the neural network training process as shown in figure 4.

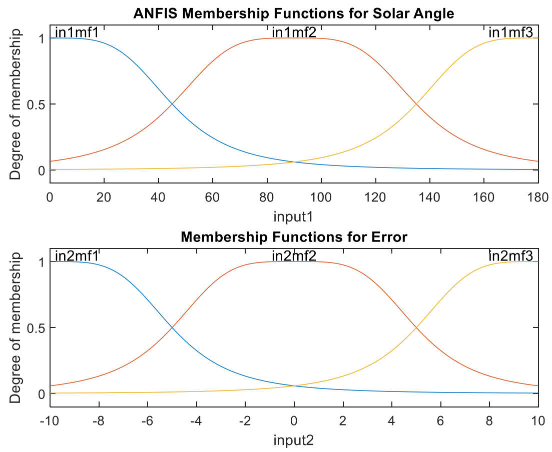

Figure 4: ANFIS Membership Function

The adaptive neural fuzzy inference system is a useful neural network method for solving problems with function approximation. A mapping relationship between the input and output data is provided by an ANFIS, where the optimal distribution of membership functions is determined using a hybrid learning method. The learning methods used in the ANFIS are a back propagation algorithm and a hybrid algorithm. The process for the prediction of ANFIS starts with defining input and output data, where input data are elevation and azimuth angle, while output data is solar radiation. In this process, all the data will be categorized into Training and Testing, and stored in a separate folder on the MATLAB workspace, and this process will be conducted before the simulation of ANFIS. Next is to load the Training and Testing data into Neuro-Fuzzy Designer in the MATLAB simulation model. Then, the process will continue with generating FIS, where in this section, several options and parameters need to be selected, such as Options for FIS generation, the number of Input MFs, and the types of membership functions used. There are four selection options available in this ANFIS simulation, and the Grid Partition system has been chosen for this study with the integration of a fuzzy logic controller into its system. Next, for the input MF, three sets of input are used, which are Five, Ten, and Fifteen MF, while for the MF type, the Gaussian membership function is selected. The various numbers of input MFs selected are used to identify the effect of this parameter on the prediction's accuracy. Other than that, the process flow continued with setting up the value of error tolerance and epoch (iteration) before the train (prediction) is simulated. The precision is achieved when the error value gained from the simulation is near or the same as the error tolerance set up. If the predicted value does not match the actual output, a new set of input MFs will be created, and the process will be repeated until the value of the output data before and after ANFIS implementation is almost the same.

3.5. Solar Tracking System Setup

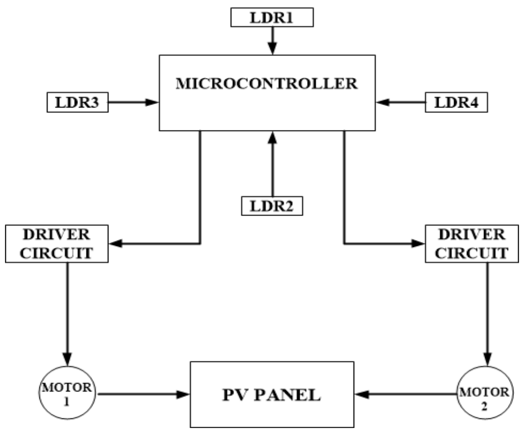

Figure 5: Block diagram of Solar Tracking System

The Solar tracking system block diagram is shown in figure 5. The light detecting circuit of the design consists of four light sensitive devices, such as LDR or phototransistors, mounted on the solar panel and placed in an enclosure. The sensors are configured in such a way that LDR_1 and LDR_2 are used to track the sun horizontally while LDR_3 and LDR_4 allow the tracking of the sun vertically. When one of the sensors receives more light than the other, the panel is not properly aligned and an error voltage results. This error voltage is used as a command to the controller to derive the motor and align the panel to be perpendicular to the sun light.

4. Results and Discussions

The simulation evaluated smart controllers for solar tracking at Kenule Beeson Saro-Wiwa Polytechnic, Bori. Morning, noon, and evening tracking results were analyzed for fixed, fuzzy, and ANFIS systems, focusing on voltage response, peak, rise time, settling, and error. Additionally, power, current, and voltage outputs were examined relative to solar angle.

4.1 Step Response Evaluation of Controllers

This section discusses the step response of the different controllers and their performance.

Table 4.1: Comparative analysis of the performance characteristics of various controllers

Controller	Fuzzy Logic Controller	ANFIS	Fixed Controller
Rising Time (s)	2	1.2	2.5
Settling Time (s)	3.2	2.8	4
Maximum Overshoot (%)	15	5	20
Peak Time (s)	2.6	1.8	3.2
Steady State Error (%)	1	0.5	1.5

The table provides a comparative analysis of the performance characteristics of various controllers, highlighting their respective strengths in terms of rising time, settling time, maximum overshoot, peak time, and steady-state error. The Fuzzy Logic Controller, with a rising time of 2 seconds and a settling time of 3.2 seconds, demonstrates a balanced response with a maximum overshoot of 15% and a steady-state error of 1%. This indicates it can manage sudden changes effectively while maintaining a reasonable level of overshoot and error.

The ANFIS Controller excels in performance, achieving the fastest rising time of 1.2 seconds and the shortest settling time of 2.8 seconds. It also features the lowest maximum overshoot of 5% and a minimal steady-state error of 0.5%, reflecting its superior ability to stabilize quickly and with precision. The peak time of 1.8 seconds further emphasizes its efficiency.

4.2 Fixed-Axis, Solar Tracker with FLC and Solar Tracker with ANFIS Controller

The final analogy in this paper was to briefly compare the results of these different tracking systems with the sole aim of finding which of them has a better performance, given all the developed models.

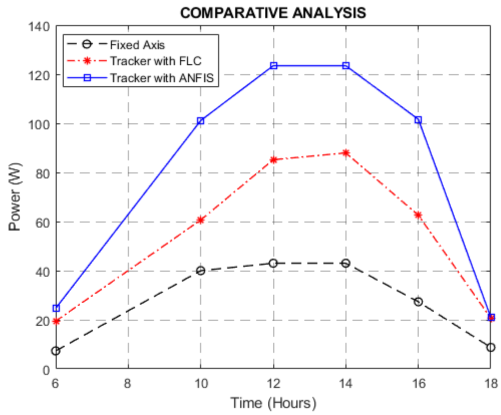

Figure 4.1: Comparison of solar panel-generated power

Figure 4.1 shows that from the tracking, ANFIS performs better than the Fuzzy logic and fixed control system.

5. CONCLUSION

This study examined the development of a controller model for an efficient solar tracking system. The following factors were considered: morning hours solar tracking, noon hours solar tracking, evening hours solar tracking, late morning hours solar tracking, and early evening hours solar tracking. The results of the input and desired output of the fixed solar tracking system, fuzzy solar tracking system, and ANFIS solar tracking system to voltage response, peak, rise time, settling threshold, and steady-state error were considered. Similarly, the results of the input and desired output of the fixed solar tracking system, fuzzy solar tracking system, and ANFIS solar tracking system to power, current, and voltage against solar angle were also considered. The results were validated and simulated using MATLAB/Simulink.

6. Future Work

The solar tracking can be optimized in the future using PSO and Genetic Algorithm (GA),

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