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Design of Automatic Two-Axis Solar Tracker with Fuzzy Logic Controller for Maximum Power System in Nigeria

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Abstract

The need of the tracking system for solar photovoltaic panel arises to extract maximum solar energy. More solar energy is collected by the end of the day if solar receivers are installed with a tracker system. In this paper, a solar tracking system is modeled using Matlab/Simulink and a fuzzy logic control is designed for the control of this system. The generated controller was combined with the solar tracking system and the control was realized with the FLC (fuzzy logic controller) in the Matlab/Simulink environment. At the same time, PID (Proportional – Integral – Derivative) control was applied to the system and the results obtained with PID control were compared with the results of fuzzy logic.

***Keywords*—Fuzzy Logic Controller, Solar Tracking System, Matlab/Simulink, Permanent Magnet DC Motor**

1.Introduction

Solar energy is rapidly gaining popularity as means of expanding renewable energy resource. Solar energy is widely available and completely free of cost. The sun is the primary source of energy. The sun produces an enormous amount of light 3.83×10^{26} watts of power in the form of light [1]

Of all the renewable energy sources available, solar energy presents itself as the most outstanding in that only in solar power do we find the potential for an energy source capable of supplying much more energy than is used [2]. By estimation, the amount of solar energy that falls to the Earth's surface in a single minute is enough to meet the World's energy demands for an entire year [3]. The earth receives 174×10^5 watts of incoming solar radiation at the upper atmosphere [4].

Nigeria, situated approximately between 4^0N and 13^0N and with landmass of 9.24×10^5 km is endowed with an annual average daily sunshine of 6.25 hours, ranging between about 3.5 hours at coastal areas and 9.0 hours at the far northern boundary and an annual average daily radiation of about 5.25 kW/m^2/day at coastal area and 7.0 kW/m^2/day at northern boundary [5]. Nigeria receives about 4.851×10^{12} kWh of incident solar energy per day or an average of 1.804×10^{15} kWh annually [3]. This annual solar energy value is about 27 times the nation total conventional energy units and it is over 117,000 times the amount of electric power generated in the country [1], these are huge energy resources.

Maximizing power output from a solar system is desirable to increase efficiency, so to maximize power output from the sun, the solar panel 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 [6]. A tracking system allows more energy to be produced because the solar array is able to remain with the sun [7]. Trackers direct the solar panels toward the sun.

Many studies have been done on the control method to fulfill the expectations in many systems including solar tracking systems. One of these studies has focused on fuzzy logic-based control. Fuzzy logic has emerged as one of the active areas of research activity particularly in control application. Fuzzy logic is a very powerful method of reasoning when mathematical model are not available and input data is not precise. Research results have shown that fuzzy logic is indeed a powerful tool, when it comes to control system or process which are complex [8].

In this paper, a solar tracking system is modeled using Matlab/Simulink and a Fuzzy logic control is designed for the control of this system. The generated controller is combined with the solar tracking system. PID (Proportional – Integral - Derivative) control is applied to the system and the results obtained were compared with the results of fuzzy logic controller. The simulation was realized using Matlab/Simulink dynamic system simulation software.

The tracking system does tracking of sunlight more effectively by providing PV (photovoltaic) panel rotation in two different axis. In dual-axis tracking system optimum power is achieved by tracking the sun in four directions. In this way we can capture more sun rays.

2. Mathematical modelling

2.1 PV Array System

In photovoltaic (PV) system, trackers help to minimize the angle of incidence (the angle that a ray of light makes with a line perpendicular to the surface) between the incoming light and the panel, which increases the amount of energy the installation produces. A solar tracker orients a solar PV panel toward the sun to maximize irradiation. The Sun's position in the sky varies both with season and time of the day as the sun moves across the sky. The solar energy intercepted by the solar panel during the course of the day is not maximized if the position of the panel is always static. Dynamically oriented solar panel can track the sun throughout each day to greatly enhance energy collection. The total hourly solar irradiation incident on the surface of a tilted PV module is give in eq.(1)

$$I = I_{ph} - I_o \left[\exp\left(\frac{V + R_s I}{cV_b\ a}\right) - 1\right] - \frac{V + R_s I}{R_p} \qquad (1)$$

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

2.3 Elevation angles (β): the elevation angle is the angle between the sun rays and the horizontal surface (solar panel). It is give in eq.(2)

$$\sin\beta = \sin\delta \sin L + \cos\delta \cos L \cos\varepsilon \qquad (2)$$

where L is the latitude angle of the location , δ is the declination angle, and ε is the hour angle.

2.4 Azimuth angle (ϕ): the azimuth angle is the angle between the true north and the projection of the sun rays on to the horizontal plane. At solar noon, the sun is always directly south in the northern hemisphere, hence the solare azimuth angle is 0^0. The azimuth angle varies throughout the day. At the equinoxes, the sun rises directly east and sets directly west regardless of the latitude, thereby making the azimuth angle 90^0 at sunrise and 270^0 at sunset. The azimuth angle can be computed using the expression in eq.(3)

$$\emptyset = 180^o + \cos^{-1}\left(\frac{\sin\beta \sin L - \sin\delta}{\cos\beta \cos L}\right) \qquad (3)$$

2.5 The actuator

The actuator chosen for the tracker is the DC motors. The motor rotates the solar panel system around the East/West and North/South axes. In order to develop a model for the motor, the electrical and mechanical aspects are considered. Considering Figure 2, and specifying the angular twist of the shaft as ϑ, the differential equations for the motor can be obtained.

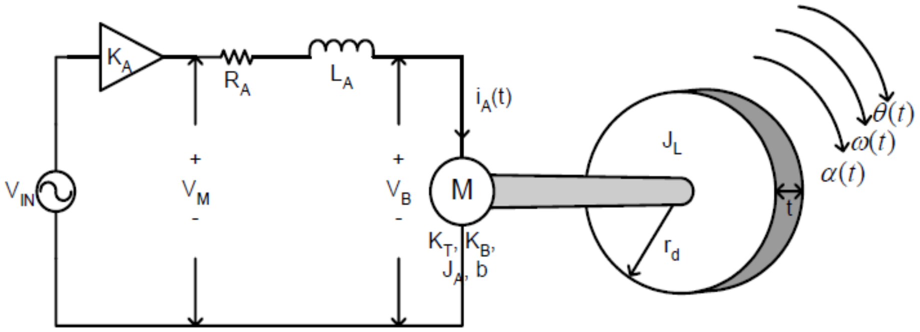

Figure 2: DC motor representation

$$V_M(t) = K_A V_{IN}(t) \quad (4)$$

$$V_M(t) = i_A(t) R_A + L_A \frac{d i_A(t)}{dt} + V_B(t) \quad (5)$$

Then,

$$V_B = K_B \omega_b(t) = K_B \frac{d\vartheta(t)}{dt} \quad (6)$$

where K_A is the amplifier voltage gain, V_M is motor input voltage, R_A is motor armature coil resistance, L_A is motor armature coil inductance, i_A is motor armature coil current, V_B is motor back EMF, K_B is motor back EMF constant, ω_b is motor shaft angular velocity, and ϑ is motor shaft position. The mechanical system include the following differential equations

$$T(t) = K_T i_A(t) \quad (7)$$

$$T(t) = J_T \propto_a (t) + b\omega_b(t) = J_T \frac{d^2\vartheta(t)}{dt^2} + b\frac{d\vartheta}{dt} \quad (8)$$

where, K_T is motor torque constant, $\propto_a$ is the motor shaft angular acceleration, and J_T is the total inertia acting on the shaft which include the motor armature inertia, gear train inertia, and the solar panels inertia.
Thus,

$$J_T = J_A + J_G + J_P \quad (9)$$

2.6 The Gear Train Inertia

With appropriate gear ratio, the motor speed can be reduced to track the 15^0/hr change of the earth as it rotates about its axis and revolves round the sun. The gear ratio of a gear train, also known as its speed ratio, is the ratio of the angular velocity of the input gear to the angular velocity of the output gear. The gear ratio can be calculated directly from the numbers of teeth on the gears in the gear train. The torque ratio of the gear train, also known as its mechanical advantage, is determined by the gear ratio.

Mathematically, if the input gear G_1 has the radius r_1 and angular velocity ω_1, and meshes with output gear G_2 of radius r_2 and angular velocity ω_2, then:

$$v = r_1\omega_1 = r_2\omega_2 \quad (10)$$

The number of teeth on a gear is proportional to the radius of its pitch circle, which means that the ratios of the gears' angular velocities, radii, and number of teeth are equal. Where N_1 is the number of teeth on the input gear, and N_2 is the number of teeth on the output gear, the following equation is formed:

$$\frac{\omega_1}{\omega_2} = \frac{r_2}{r_1} = \frac{N_2}{N_1} \quad (11)$$

This shows that a simple gear train with two gears has the gear ratio *R* given by

$$\frac{\omega_1}{\omega_2} = \frac{N_2}{N_1} \quad (12)$$

This equation shows that if the number of teeth on the output gear G_2 is larger than the number of teeth on the input gear G_1, then the input gear G_1 must rotate faster than the output gear G_2.

The total system inertia as

$$J_T = J_A + J_{G1} + \left(\frac{N_1}{N_2}\right)^2 \left[J_{G2} + J_{G3} + \left(\frac{N_3}{N_4}\right)^2 \{J_{G4} + J_P\}\right] \quad (13)$$

Substituting Eqs.(4) and (6) in (5), we obtain

$$K_A V_{IN}(t) = i_A(t) R_A + L_A \frac{di_A(t)}{dt} + K_B \frac{d\vartheta(t)}{dt} \quad (14)$$

Also, substituting Eqs. (7) into (8), we have

$$K_T i_A(t) = J_T \frac{d^2\vartheta(t)}{dt^2} + b\frac{d\vartheta}{dt} \quad (15)$$

Applying Laplace transforms to Eqs.(14) and (15),

$$K_A V_{IN}(s) = I_A(s) R_A + L_A s I_A(s) + K_B s\vartheta(s) \quad (16)$$

$$K_T I_A(s) = J_T s^2 \vartheta(s) + bs\vartheta(s) \quad (17)$$

Making I_A subject of the formula in Eq. (17) and substituting the same in equation (16), the final transfer function for the solar tracker drive mechanism is expressed as

$$\frac{\vartheta(s)}{V_{IN}(s)} = \frac{K_T K_A}{J_T L_A s^3 + (J_T R_A + bL_A)s^2 + (bL_A + K_T K_B)s} \quad (18)$$

3 Design process of the proposed controller

In most research literature, a fuzzy controller system is commonly defined as a system that emulates a human expert. In this case, the knowledge of the human operator would be put in the form of a set of fuzzy linguistic rules. These rules would produce an approximate decision in the same manner a human would do [9]. A block diagram of a fuzzy control system is shown in figure 3.

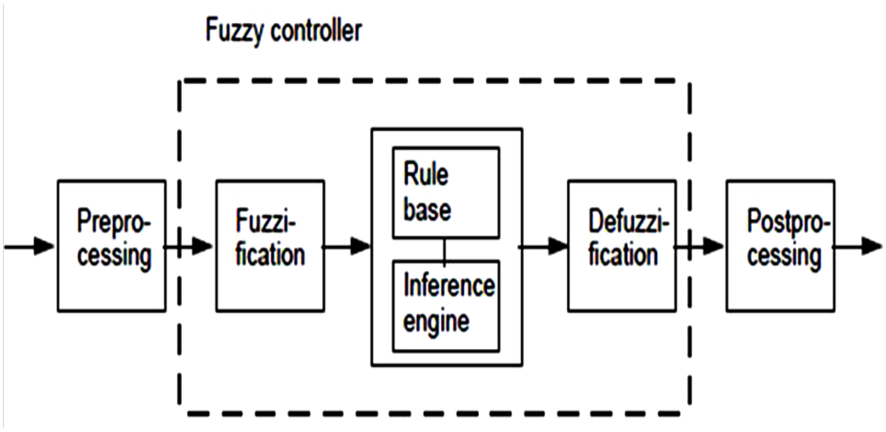

Figure 3: Fuzzy logic controller system

The fuzzy controller is composed of the following four elements. These are fuzzification, rule base, inference mechanism and defuzzification. A fuzzification interface converts the crisp inputs into the fuzzy membership values. A rule base consists of a data table which includes information related to the system. An inference mechanism emulates the expert's decision making in interpreting and applying knowledge. A defuzzification interface converts the conclusions of the inference mechanism into the crisp inputs for the process. The values of error (e(k)) and its change (Δe(k)) occurring during the operation of the system form the crisp inputs of the system.

4 Models experimentation and simulation

In this paper, a virtual modeling environment called MATLAB and Simulink was employed in experimentation and analysis of the mathematical models developed in the previous sections. It is worth mentioning here that the solar panel, solar angles, solar tracker, PID controller and FLC controller form the frame work of the entire system. The essence of the simulation is to carry out a comparative study in order to determine the effectiveness of the designed controller.
To realize this continuous-time transfer function model, the parameters in Table 1 were inserted into Eq.(18)

The input to the tracker mechanism is a 48V voltage to energize the two PMDC motors responsible for delivering required slew rate through gear mechanism, while the output is the angular position. The tracker was simulated for 24 hours separately to assess its response and also determine how the PID controller tuning parameters and Fuzzy Logic controller universe of discourse.

Table 1: Solar tracker system parameters

Parameters	Values
Terminal voltage	48V
Speed	1500rpm
Torque Constant	0.1112Nm/A
Electron Charge	1.607×10^{-19}C
Amplifier Voltage Gain	1.38V/m
Back EMF constant	0.1098
Armature Coil Inertia	3.7×10^{-5}kgm^2
Inductance	0.13H
Resistance	0.5Ω
Total Inertia of Gears	87.60kgm^2

5 Experimental Results and Discussions

The first aspect was to simulate the system without any tracking mechanism attached to it to test the functionality of the designed PV cell array with the sole aim of studying the P-V (power-voltage) and I-V (current-voltage) characteristics of the solar cells. Thereafter, the two-axis tracking system was incorporated and tested with PID controllers for controlling the positions of the solar arrays in the horizontal and vertical planes. Besides, fuzzy logic controllers were introduced within the system to equally assess their performances. The final analogy was to briefly compare the results of this different tracking system with the sole aim of finding which of them has a better performance given all the developed models. It is important to display the values of the solar panel generated insolation and power as illustrated in tables 2 and 3

Table 2: Solar insolation generated for different tracking systems

Solar Insolation (W/m^2)			
Time (Hours)	Fixed-Axis Tracking	Two-Axis with PID	Two-Axis with FLC

6	350.0	1434.5	2151.8
7	406.0	1452.6	2178.8
8	956.0	1526.2	2288.9
9	1118.0	1674.0	2510.0
10	1189.7	1926.9	2887.7
11	1223.6	2278.3	3411.3
12	1234.0	2491.5	3728.0
13	1223.6	2278.3	3411.3
14	1189.7	1926.9	2887.7
15	1118.0	1674.0	2510.0
16	956.0	1526.2	2288.9
17	406.0	1452.6	2178.8
18	350.0	1434.5	2151.8

Table 3: Panel power generated for different tracking systems

Panel Power (W)			
Time (Hours)	Fixed-Axis Tracking	Two-Axis with PID	Two-Axis with FLC
6	0	0	0
7	4.6710	16.7112	89.7
8	51.7062	82.5416	197.6
9	105.8849	158.5394	355.8
10	159.3134	258.4786	625.8
11	209.9219	392.2322	1087.7
12	254.4739	518.2208	1543.1
13	291.8805	547.2472	1500.0
14	314.2814	513.4247	1227.8
15	311.1767	470.7487	1041.3
16	251.9661	407.0925	763.2
17	50.0771	180.3950	4976
18	6.7500	38.8640	132.3

The Table 3 provides a comparison between output powers for three cases. Note that the simulation of the fixed system was made possible the Simulink modelling and simulation environment. All the performance curves for these systems are shown in figures 4, and 5, respectively.

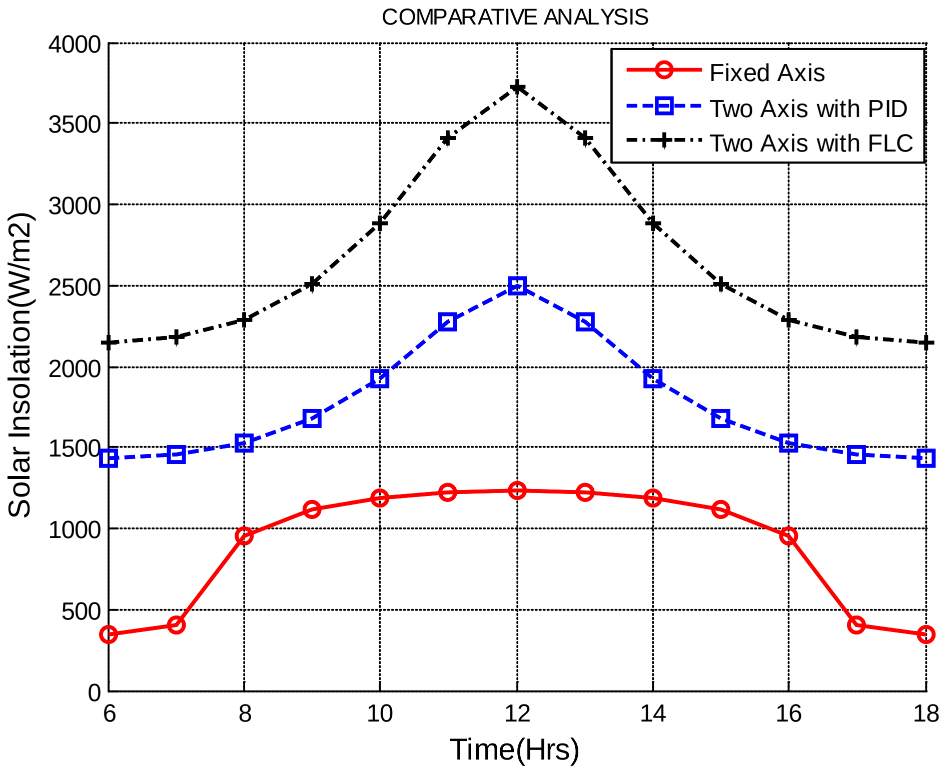

Figure 4: Comparison of solar insolation

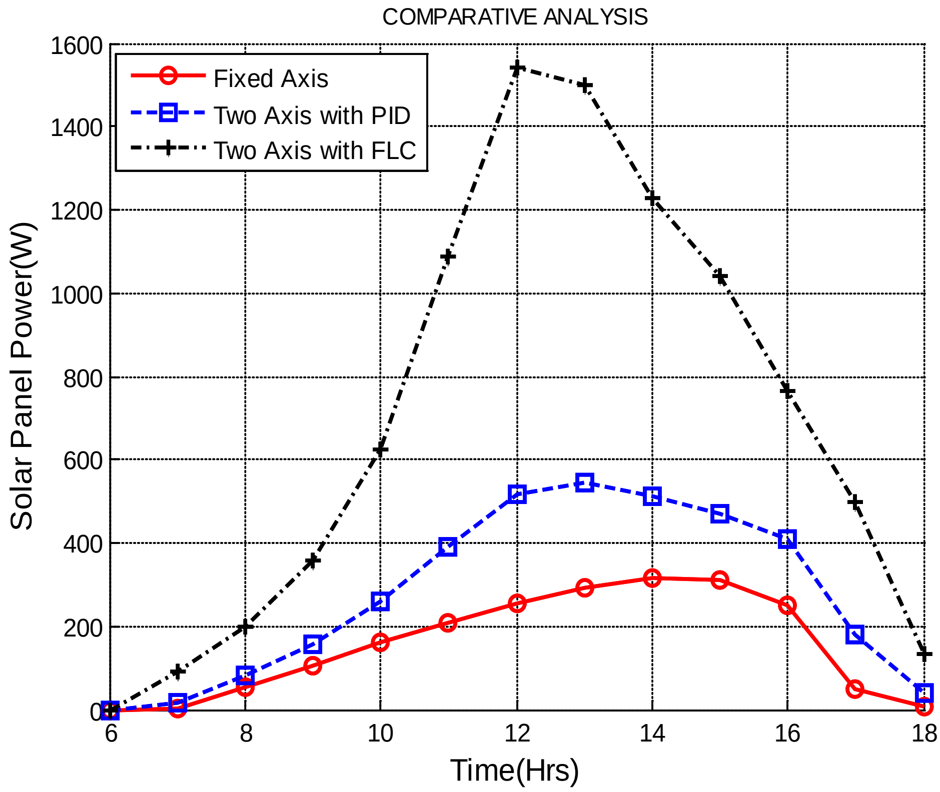

Figure 5: Comparison of solar panel generated power

Figure 4 shows the insolation on the panel, this insolation caused the designed PV cells to generate current and voltage thereby producing a remarkable quantity of power. At the maximum insolation of 3700W/m^2 the solar array with FLC was able to generate a maximum power of 1500W which occurred at midday. The solar panel power curve in Figure 5 showed a maximum attainable power of 1500W with FLC and 550W with PID which is higher than the rated power of the PV cells array.

6 Conclusion

In this paper, a solar tracking system was designed for Matlab/Simulink environment and a control method was proposed for the system. The results from the simulation of the fixed-axis system, two-axis system controlled by PID controllers, and two-axis system controlled by FLC controllers showed that FLC controllers performed much more than the other two.

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