# Modelling and Control of an Experimental Fuzzy Logic Controlled Dual-Axis Solar Tracking System based on Field Programmable Gate Array

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**ABSTRACT**

This paper aims to model and control of an experimental dual axis solar tracking system utilizing a Field Programmable Gate Array (FPGA) based on intelligent control system design. The proposed system is a real-time solar tracking system which capable of precisely aligning with the sun's position to maximize solar energy harvesting efficiency. Solar energy plays a distinctive role as a primary source of new and renewable energy due to its clean energy and does not pollute the environment. As a result, this research presents an advance in one of the important ways to increase energy productivity from solar cells such as dual axis solar tracker system. The proposed system is controlled through Fuzzy Logic Control (FLC) based on FPGA platform. To prove the efficiency of applying the dual-axis solar tracker based on fuzzy control, its results were compared to the fixed system of solar panel, and the two-axis solar tracker proved its distinction and efficiency in raising solar production by 21%, which gives preference in its application and exploitation in solar systems.

***Keywords***: *Solar Tracker; FPGA; FLC; Dual Axis Linear Actuator; Sinai University Campus, Arish, North Sinai, Egypt.*

## 1. Introduction

Solar energy has emerged as a crucial renewable energy source, offering a sustainable and eco-friendly alternative to conventional fossil fuels [1]. To optimize solar energy harvesting efficiency, solar tracking systems have been extensively researched and implemented. These systems dynamically adjust the orientation of solar panels to continuously face the sun, maximizing energy capture throughout the day [1-6]. In this literature review, we explore relevant research on the modelling and control of dual-axis solar tracking systems based on FPGAs. Numerous studies have showcased the advantages of solar tracking systems over fixed solar installations. Algarni and Al-Maashri [1] conducted a comparative analysis between static and dual-axis tracking systems, revealing that the latter could improve energy generation by up to 35% in certain geographic locations. This emphasizes the potential of dual-axis solar tracking systems in maximizing energy output, particularly in regions with significant variation in solar incidence angles throughout the day.

The ever-increasing demand for clean and sustainable energy sources has fueled extensive research in the field of renewable energy systems. Among these, solar energy has emerged as a promising and environmentally friendly solution to address the global energy crisis. Solar tracking systems, which dynamically adjust solar panel orientation to align with the sun's position, have garnered significant attention due to their ability to enhance solar energy harvesting efficiency [1].

In their study, Atas and Bayhan [7] developed a mathematical model and control system for a two-axis solar tracker, validating its effectiveness through real-time laboratory experiments. This research demonstrated the feasibility and efficiency of the proposed control algorithm for precise sun tracking. Accurate modelling of the solar tracking system is crucial for effective dual-axis solar tracking. Pohl and Fathabadi [8] presented a comprehensive kinematic and dynamic model of a dual-axis solar tracker, considering factors such as sun position, panel orientation, and tracking errors. Such mathematical models serve as a foundation for developing robust control algorithms and predicting solar tracker behavior in real-time. For achieving precise sun tracking, the selection and design of appropriate control algorithms play a pivotal role. While classical control techniques like PID have been widely employed for solar tracking, fractional-order PID (FOPID) controllers have shown superiority in handling system nonlinearity and disturbances. Hassan et al. [9] proposed an optimal FOPID controller design for dual-axis solar tracking using a genetic algorithm, demonstrating its effectiveness in mitigating nonlinearity and disturbances, leading to enhanced energy harvesting efficiency. Additionally, FLC has gained popularity for its ability to handle uncertainty and adapt to changing environmental conditions [10]. Esen and Inalli [11] compared the performance of different fuzzy logic controllers for dual-axis solar tracking systems, highlighting the adaptability and robustness of fuzzy logic controllers in ensuring accurate sun tracking and increased energy harvesting efficiency.

The adoption of FPGA technology in solar tracking control has gained momentum due to its re-configurability and parallel processing capabilities. Kar et al. [12] demonstrated FPGA's efficiency in implementing complex control algorithms, ensuring real-time performance and low-latency responses for the solar tracking system. The FPGA-based approach allows for flexible implementation and adaptation of control algorithms, making it a suitable choice for real-world applications.

In conclusion, the literature review highlights the significance of modelling and control in dual-axis solar tracking systems based on FPGAs. Past research has shown the potential of dual-axis tracking to enhance energy capture, and various control algorithms, such as PID, FOPID and FLC, have been explored for their efficacy. The integration of FPGA technology into solar tracking systems provides a promising avenue for real-time control and opens new possibilities for improving solar energy harvesting efficiency in practical applications. This literature review provides valuable insights for the proposed research paper, aiming to further advance solar tracking technologies and improve renewable energy systems' overall performance.

### 1.2 Research objectives

This research paper introduces a comprehensive investigation on the modelling and control of an experimental FLC for dual-axis solar tracking system (DASTS) based on FPGA. The primary objective of this study is to design and implement an advanced solar tracking system that can accurately follow the sun's path in both azimuth and elevation angles, thereby maximizing solar energy capture throughout the day. The motivation behind this research stems from the potential of solar tracking systems to significantly boost energy yields compared to static solar installations. Traditional fixed solar panels only operate optimally when the sun is perpendicular to their surface, resulting in suboptimal energy generation during other periods of the day. In contrast, dual-axis solar tracking systems continuously reposition solar panels to maintain an optimal angle with the sun, ensuring higher energy output and improved overall system efficiency.

## 2. Aim and Research Significance

This research paper aims to contribute to the advancement of solar tracking technologies by combining sophisticated control algorithm with FPGA-based real-time processing. The outcomes of this study will provide valuable insights into improving solar energy harvesting efficiency, ultimately fostering the adoption of dual-axis solar tracking systems for a greener and sustainable future.

## 3. System Modelling

The proposed research is structured based on a foundation of mathematical modelling and control algorithm development. The dual-axis solar tracker's kinematic and dynamic modelling will be carried out to precisely predict the sun's position at any given time, allowing for accurate positioning of the solar panels [7].

The equivalent circuit for photovoltaic panels is shown in Figure 1. The analysis of the circuit is described in below Equations. The system is modeled as explained in Equations 1-11.

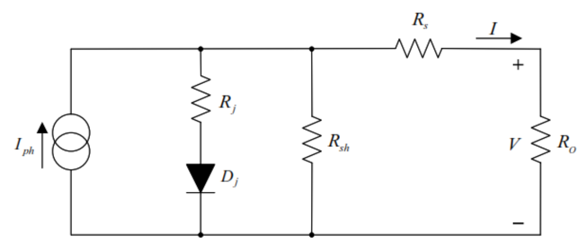


Figure 1. Equivalent circuit of PV system

$$I = I_{ph} - I_0\left(e^{\frac{V_d}{V_T}} - 1\right) - \left(\frac{V + R_{pv} I}{R_{sh}}\right) \quad (1)$$

$$V_d = V + IR_{pv} \quad (2)$$

$$V_T = \frac{T K n}{q} \quad (3)$$

$$I = I_{sc}\left[1 - c_1\left(e^{\frac{V - V\Delta}{c_2 V_{oc}}} - 1\right)\right] + I\Delta \quad (4)$$

$$c_1 = \left(1 - \frac{I_m}{I_{sc}}\right) e^{\frac{-V_m}{c_2 V_{oc}}} \quad (5)$$

$$c_2 = \frac{\frac{V_m}{V_{oc}} - 1}{\ln\left(1 - \frac{I_m}{I_{sc}}\right)} \quad (6)$$

$$I\Delta = I_{hp} - I_{sc} \quad (7)$$

$$I_{hp} = \frac{S}{S_{ref}}\left(I_{sc} + K_1\, I\Delta\right) \quad (8)$$

$$V\Delta = R_{pv} I\Delta - K_v\, T\Delta \quad (9)$$

$$T\Delta = T - T_{ref} \quad (10)$$

$$P = VI \quad (11)$$

The sensors used in this study is the Light Dependent Resistor (LDR). It is used to measure the incident light to obtain the optimum angle of rotation [4]. The relationship between the input and output of LDR can be expressed as follows:

$$log(R) = -3/4 * \log(I_{eff} + 5) \quad (12)$$

To determine the effective light intensity value obtained over the course of one day, we can calculate it using the following formula, where $I_{eff}$ represents the intensity of solar light, R is the electrical resistance, $I_{max}$ is the maximum intensity value for each LDR, and $\theta_{eff}$ is the angle of incidence of solar radiation that determines the effective light intensity:

$$\mathrm{I_{eff}} = \mathrm{I_{max}} * \sin(\theta_{\mathrm{eff}}) \quad (13)$$

The Linear Actuator is used to move the panels for up or down and right to lift [6]. The linear actuator is modelled mathematically as given in Equation (14). Besides, the Matlab/ Simscape model of the actuator is shown in Figure (2).

$$\frac{X(s)}{E_a(s)} = \frac{K_t}{P\,[\left(J_m s^2 + D_m s\right)\left(R_a + L_a s\right) + K_t K_b s\,]} \quad (14)$$

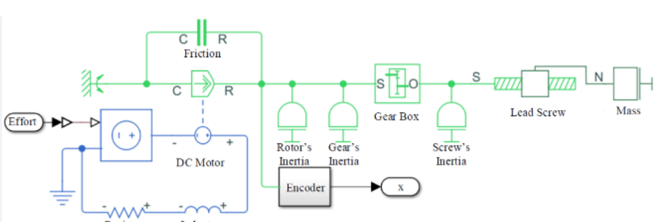


Figure 2. Matlab/ Simscape model for linear actuator

## 3. Experimental Hardware System

The experimental system is built based on different components and equipment (see Figure 3). The experimental set-up includes one test rig of DASTS and it is described as following: Closed Loop, Sensor Based, Dual Axis, Azimuth – Altitude, Microprocessor & Elecro-Optical Sensor, Solar Tracker.

The experimental setup will be deployed in Sinai University Campus, Arish, North Sinai, Egypt, has coordinates of +31.13 (31°07'48"N), +33.8 (33°48'00"E) [13]. The research was conducted on November 2021 where it consist of 4 mm iron base with 1.45 m width and 1.65 m height metal frame, two 150 watt polycrystalline PV panels, two 1,780 Newton, 0.76 m stroke, 7.62 mm/sec linear actuator DC motors, Signal Conditioner Arduino Uno R3 Board, and four light-dependent resistors. The performance evaluation of the FPGA-based control algorithm will be carried out under real-world solar conditions, and the results will be compared against fixed solar systems. The chosen FPGA platform, featuring the Xilinx Spartan-7 XC7S15 chip, will serve as the core of the control system. FPGA technology offers high flexibility and real-time processing capabilities, making it well-suited for the implementation of sophisticated control algorithms. This will enable the tracking system to adapt to varying environmental conditions and ensure seamless operation under different scenarios.

Figure 3. Experimental test rig overview for DASTS

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### 4. Tracking Approach

The description of tracking system is demonstrated in Figure 4. The tracking approach relies on comparing pairs of LDR sensors positioned around the axes of rotation (See Figure 4.). Specifically, LDR sensors 1 and 2, denoted as VE_1 and VW_2, respectively, are responsible for managing the rotation of the primary axis (Zenith angle) through Pitch Motor 1. Conversely, LDR sensors 3 and 4, labeled as VN_3 and VS_4, respectively, are utilized for controlling the rotation of the secondary axis (Azimuth angle) via Yaw Motor 2. When assessing each pair of LDR sensors, the actuator is engaged upon detecting a discernible difference in solar radiation intensities. Conversely, rotation halts when there's no appreciable variance in solar radiation intensities.

Importantly, a safety margin is incorporated into the tracking decision process, designed to prevent oscillations around the sun's position [2]. As a result, this study establishes a predefined threshold for the difference between intensities registered by the LDR sensors, set at 10 for both axes of rotation. When the disparity falls below this established threshold, the system maintains its current position [14]. However, if the difference equals or surpasses the defined threshold, the system then aligns itself with the sun's position based on the tracking strategy. This strategy triggers tracking signals, enabling the operation of motorized linear actuators via an L298N motor drive board. It's worth noting that while the tracking strategy activates the axes of rotation, the solar tracking system has built-in limitations, and it cannot exceed the designated angular fields, as constrained by limit switches.

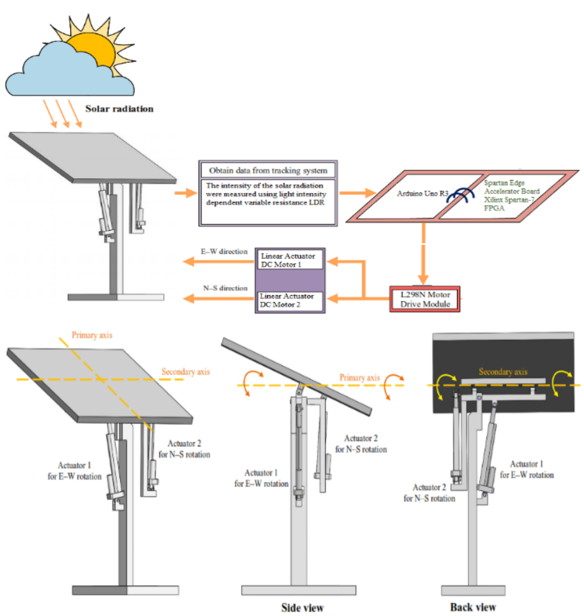



Figure 4. Description of tracking system approach

It's very important to know that the solar radiation intensity data obtained from measurements may occasionally contain noise or errors stemming from device malfunctions or environmental factors. In this research, the gathered data is subjected to preprocessing before applying the tracking strategy to eliminate any noise caused by electronic devices or environmental conditions [4]. Following this preprocessing step, the refined data is then provided to the tracking strategy for the purpose of accurately tracking the sun's position.

### 5. Fuzzy Logic Control (FLC)

Fuzzy logic control is a type of control system that employs fuzzy logic to make decisions based on imprecise or uncertain data [15]. It finds particular utility in scenarios where traditional control systems may prove ineffective, particularly in managing complex or nonlinear systems. FLC operates by utilizing linguistic variables, which facilitate more natural and intuitive control of the system [16]. This mathematical system evaluates analog input values in terms of logical variables that can assume continuous values between 0 and 1, in contrast to classical or digital logic, which operates with discrete values of either 1 or 0 (true or false, respectively) [17].

The implementation of FLCs can be accomplished through a range of programming languages, including MATLAB, Python, and C++. Additionally, there are various libraries and frameworks available for the development of FLCs, such as the Fuzzy Logic Toolbox designed for MATLAB [5, 18]. Figure 5 demonstrates the structure of FLC with the system including sensors. Besides, block diagram of solar tracker system that controlled by FLC is given in Figure 6 [8, 10, 11].

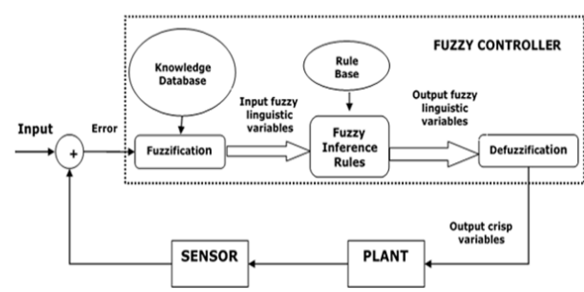



Figure 5. Integration of fuzzy controller with the system

The explanation of the components of FLC is demonstrated in the following points [14-16, 18]:

**Input:** This phase involves parameters such as the count of input signals, the number of derivatives for each input signal, and the scaling of these input signals.

**Fuzzification:** This step encompasses aspects like the types of membership functions employed, characteristics like mean, distribution, and peak values of these membership functions, symmetry considerations, intersection points, and the total count of membership functions.

**Rules:** In this stage, one needs to determine the number of rules in the system, define the structure of these rules, and assign appropriate weights to these rules.

**Rule evaluation:** This part encompasses the selection of aggregate operators and conclusion operators for evaluating the rules.

**Aggregation:** Aggregation entails the process of combining operators with the outcomes of each rule and the conclusions drawn from each rule.

**Defuzzification:** During this phase, a procedure is utilized to transform fuzzy values into definitive, assertive values.

**Output:** This section pertains to the specification of the number of output signals.

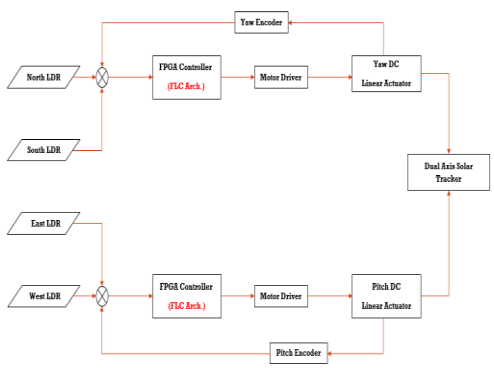
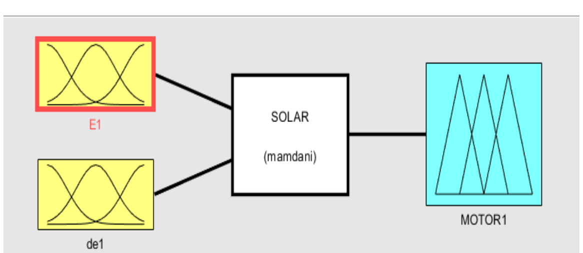
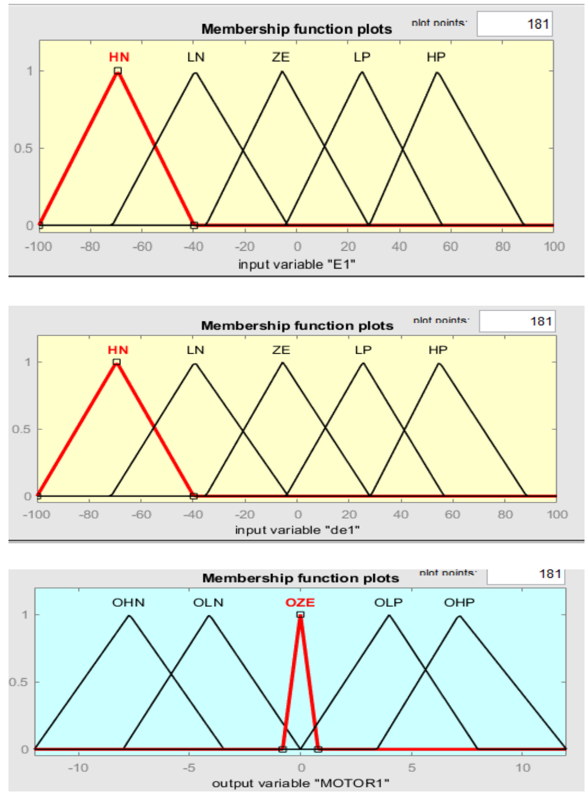


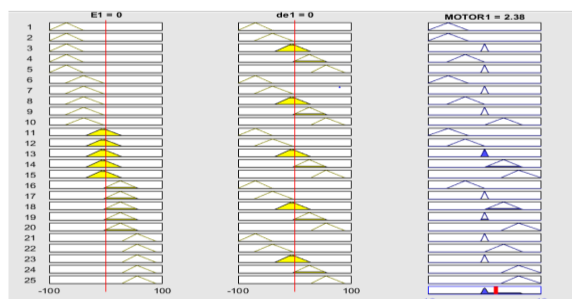

Figure 6. Block diagram of solar system with FLC



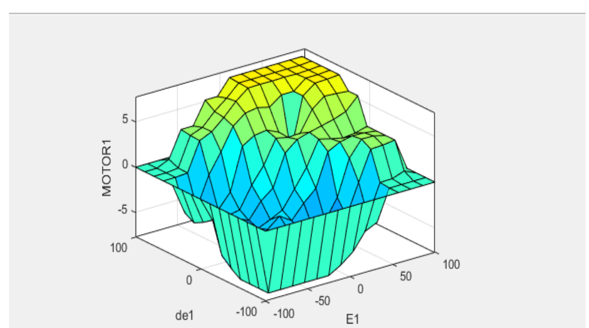

(a) FLC system for the tracker based on Mamdani inference system.




(b) Triangle MFs for inputs and outputs




(c) Rule viewer for the inputs and outputs




(d) Surface viewer of error and change of error

Figure 7 Details of FLC

Based on different trails and tests, the used type of membership functions for both inputs and outputs are triangle membership functions (see Figure 7). The inputs of the FLC are chosen to be the error and change of errors.

## 6. Test Results and Discussion

Four LDR sensors are strategically placed corresponding to the axes of rotation. The analog data collected by these LDR sensors is then sent to an Arduino UNO R3 microcontroller board, serving as a signal conditioning unit. Subsequently, this analog LDR sensor data is subjected to processing and analysis to facilitate decision-making for the solar tracking system, guided by the tracking strategy explained later in this document. This data is transmitted via the Spartan Edge Accelerator Board, which is equipped with the Xilinx Spartan-7 XC7S15 FPGA microcontroller board. The proposed system consist of two PV panel have the same power (150 watt for each other), mechanical and electrical characteristics (See Figure 8).

In this article, different measuring devices are used to measure various quantity to help us to evaluate the performance of the suggested system in PV systems. The used measuring devices are solar power meter (TM-206) and multi meter device (DT-9205B). The solar power meter is a device employed for quantifying the power per unit area of incoming solar radiation that reaches the meter's sensing region. In addition, the multi-meter is a versatile tool commonly utilized in electronic hardware workshops and electronics laboratories. It serves the purpose of measuring various electrical properties, encompassing voltage, resistance, and current, making it an essential instrument for a wide range of electronic applications.

Figure 8. Two PV panel (2*150 watts)

The procedure of obtaining the results, make sure that the devices are calibrated and ready to be used. Then, make sure that a dual axis tracker is work correctly. The data are collected from 08:20 AM to 16:22 PM. The collected data include the measuring of intensity of solar radiation, open circuit voltage and short circuit current for both moving and fixed PV-Panel at the same time and the same condition. After that, the maximum power is calculated based on the following equation,

$$P_{max} = V_{oc} * I_{sc.} \quad (15)$$

### 6.1 Scenario (1): Movable and Fixed PV Panel

The majority of photovoltaic (PV) power plants are traditionally designed with fixed installations. However, it's worth considering that it's feasible to generate a greater amount of energy using the same number of PV panels and inverters. Therefore, we conducted a comparison between a stationary PV panel setup and a mobile PV panel setup mounted on a dual-axis tracker, which is governed by a combination of FPGA and Fuzzy Logic control.
This section present a discussion and analysis of the outcomes derived from experimental test rig system. The results are visually represented through graphs, enabling a clear comparison between stationary and mobile PV panels (see Figures 9, 10, 11, 12) . Figure 9 shows the open circuit voltage for fixed and movable panels, while Figure 10 demonstrates the results of short circuit currents for two types. Besides, Figure 11 depicts the intensity for solar radiation for fixed and dual axis solar system. In addition, the output PV power for fixed and movable panels is

shown in Figure 12. Table 1. provided illustrates the correlations among voltage, current, power, and solar radiation concerning both the Moving and Fixed PV Panels, all observed at the specified time intervals detailed in the schedule. The units of time, power, current, voltage and solar radiation in this paper are hour (h), watt (w), ampere (A), voltage (v) and W/m$^2$ respectively.

Table 1. Measured data of movable and fixed panels

| Hours | Voc | | Isc | | P=VI | | G | |
|---|---|---|---|---|---|---|---|---|
| | Fixed | FLC | Fixed | FLC | Fixed | FLC | Fixed | FLC |
| 8:20 | 20.41 | 20.55 | 7.27 | 7.82 | 148.3807 | 160.701 | 865 | 1105 |
| 9:32 | 20.5 | 20.65 | 7.34 | 7.93 | 150.47 | 163.7545 | 900 | 1108 |
| 10:36 | 20.53 | 20.67 | 8.25 | 9 | 169.3725 | 186.03 | 1004 | 1112 |
| 11:27 | 20.59 | 20.79 | 8.89 | 9.08 | 183.0451 | 188.7732 | 1074 | 1125 |
| 12:01 | 20.69 | 20.81 | 9.03 | 9.12 | 186.8307 | 189.7872 | 1103 | 1126 |
| 12:44 | 20.53 | 20.71 | 8.88 | 9.05 | 182.3064 | 187.4255 | 1079 | 1120 |
| 13:28 | 20.41 | 20.6 | 8.27 | 9.04 | 168.7907 | 186.224 | 991 | 1117 |
| 14:36 | 20.31 | 20.5 | 6.91 | 8.86 | 140.3421 | 181.63 | 850 | 1100 |
| 15:45 | 20.1 | 20.3 | 4.97 | 8.51 | 99.897 | 172.753 | 587 | 1040 |
| 16:22 | 19.59 | 19.89 | 3.66 | 6.65 | 71.6994 | 132.2685 | 350 | 837 |

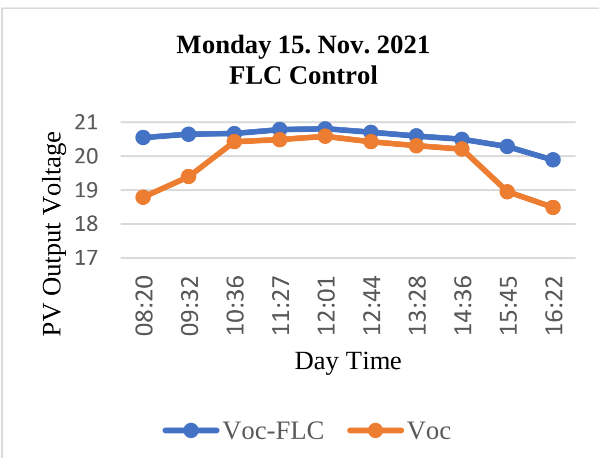



Figure 9. Comparison between fixed and movable open circuit voltages.

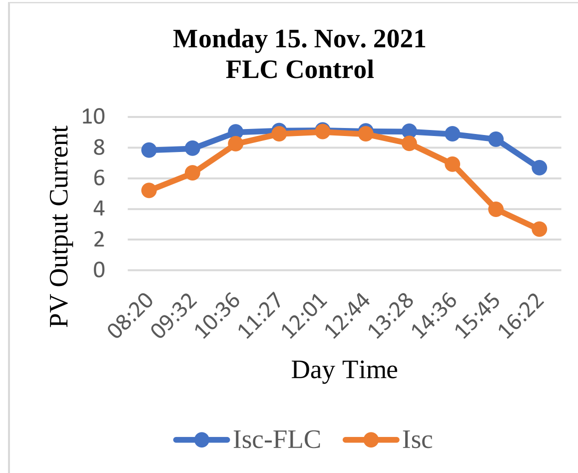



Figure 10. Comparison between fixed and movable short circuit currents.

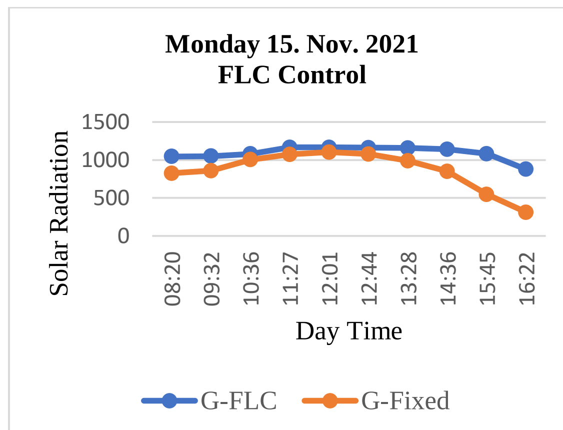



Figure 11. Comparison between fixed and movable intensity of solar radiation (W/m$^2$).

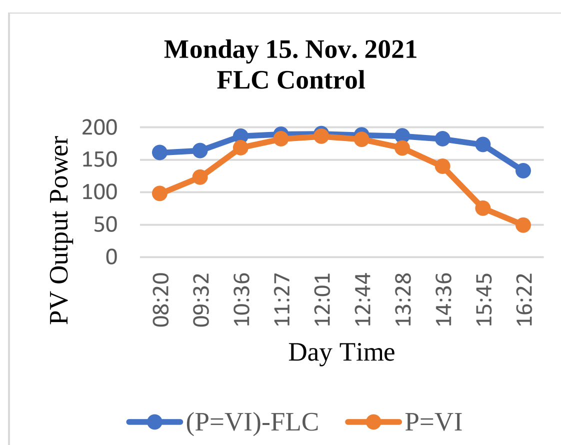



Figure 12. Comparison between fixed and movable PV output power

Considering results in Table 1 and Figures 9-12, it is very clear that trackers generate more electricity power than their fixed counterparts due to increased direct solar radiation. Besides, voltage and current are affected by the intensity of solar radiation, there is a direct relationship between them. The maximum power reached at 12:01 in the two systems. In addition, the two systems were close to each other in the period from 11:27 to 12:44. This is due to the perpendicularity of the solar radiation and the convergence of the angles of inclination of the two systems.

## 7. Conclusions

The dual axis tracker for PV system is implemented in this paper. The experimental system is structured based on the interface of FPGA board as the core of control system which collect the signals from sensors then processing them to give a suitable control signal to the actuators of the system. The intelligent FLC approach is applied to the system for dual axis solar tracker system. In addition, a deep scenario is carried out in this paper to produce a comparison study between fixed and movable tracker PV system. The comparison is introduced to check the effectiveness of the FLC based dual axis system. The results show that the FLC based dual axis system produced greater PV power than the case of fixed system.

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