International Research Journal of Advanced Engineering and Science
ISSN (Online): 2455-9024

An Experiment– Based Approach of Smart Dual Axis Sun Tracking System for Optimizing Photovoltaic Energy Production in Variable Weather Conditions

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Abstract*— In the modern era, solar energy stands out as a highly reliable alternative energy source. Extensive research efforts are being dedicated to enhancing the efficiency of photovoltaic (PV) systems, aiming to establish their competitive edge among other available renewable energy sources. Photovoltaic panels are employed to harness solar or visible light energy and convert it into electrical energy. However, the energy production of these fixed-angle photovoltaic panels is inherently inefficient. This challenge can be effectively addressed by employing a sun tracking PV panel system. This master's thesis presents the design and development of an intelligent dual-axis solar tracker that incorporates a remote monitoring and control system, enabling unlimited distance adaptability. The solar tracker encompasses three essential components: the electronics circuit, mechanical subsystem, and microcontroller programming. These components have been meticulously integrated and realized in a four-step process comprising coding, circuit design simulation using the Arduino Integrated Development Environment (IDE) in conjunction with Proteus Virtual System Modelling (PVSM), physical implementation on a breadboard, component soldering on an electronic board, and system packaging to create a prototype. The solar tracker exhibits very good capabilities, enabling sun tracking within 360 degrees in the East, West, North, and South directions. Experimental results indicate a significant increase in power generation using the solar tracker compared to a fixed PV module system, with a percentage power gain of up to 54.72% on cloudy days and 70.02% on brighter sunny days. These findings emphasize the potential of solar trackers to enhance the efficiency and performance of photovoltaic systems, thereby advancing the utilization of solar energy as a sustainable and competitive renewable energy source.*

Keywords*— Photovoltaic Energy, Smart system, Dual-axis Solar tracker, Arduino cloud, light depending resistor, ESP32, and Arduino UNO microcontrollers.*

I. INTRODUCTION

In today's world, electricity is the backbone of our day and night activities; we need electricity as essential as humans need water to live. However, the major challenge lies in the energy sources used to generate this electricity, with some being very harmful to the environment, human health, and animals. Despite the inherent advantages and disadvantages of energy sources, there is a global shift towards renewable energy sources, which are more environmentally friendly. This transition is driven by the need to meet increasing electricity demands while mitigating environmental impact (Harsh et al., 2022; Zhang et al., 2022; Castillo-Calzadill et al., 2022).

Renewable energy, often referred to as clean energy, is derived from natural sources that are continuously replenished by nature. These sources include solar energy, wind energy, hydro energy, tidal energy, geothermal energy, and biomass energy. In contrast, non-renewable energy sources, such as nuclear energy and fossil fuels, are finite and contribute to environmental degradation, including climate change and global warming (Yong et al., 2023).

Despite the challenges, there is a growing adoption of renewable energy sources worldwide. The International Energy Agency (IEA) reports a significant increase in renewable energy capacity additions, with an increase of 6% to almost 295GW in 2021 and an increase of over 8% in 2022, reaching almost 320GW, with solar energy expected to account for a substantial portion, about 60% of this growth (Citaristi et al., 2022). In the case of Cameroon, the total installed electricity generation capacity at present is approximately 1402MW, with 56.16% from renewable energy and 43.84% from non-renewable sources. Moreover, an investigation of the solar irradiance potential in Cameroon underscored that the mean solar irradiance is roughly 5.8 kWh/m2/day in the northern regions, while it's in the range of 4.0–4.9kWh/m2/day in the southern regions of the country. Given the massive available solar energy potential in Cameroon, the Government of Cameroon (GoC) has recognized the importance and potential of the promising photovoltaic energy feature and is committed to boosting the solar energy sector by ambitious projects, such as the "Cameroon 2020 Photovoltaic Power Project," aimed at harnessing solar energy to meet electricity demands and improve energy access. This project aims to create a capacity of 500MW from photovoltaic energy (Kidmo et al., 2021).

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Among renewable resources, solar energy stands out as the most vital due to its wide accessibility and numerous advantages compared to other renewable energy sources (Tukymbekov et al., 2019). Several review articles have discussed the potential of solar energy as a major alternative to conventional energy sources. For instance, Perez-Mora et al. (2018) summarized the literature available on solar district heating and identified the technical and economic issues in its widespread application. Solar energy refers to the energy harvested directly from the sun. Each day, the sun emits a massive amount of energy onto the Earth's surface, estimated at about 172,000TWh per hour, more than sufficient to meet the world's energy demands if properly harnessed (El Hammoumi et al., 2022). Photovoltaic panels convert solar energy into electrical energy or thermal energy through a phenomenon known as the photovoltaic effect. Moreover, photovoltaic modules made today are unable to operate with full efficiency due to natural effects on the panels and the materials used in fabricating them. The major factors that influence the panel's efficiency are temperature, irradiation, and dust. This problem can be solved by various techniques such as the solar tracker system, MPPT controller technique, cooling system technique, cleaning system technique, and floating system technique. Solar energy relies heavily on sunlight, making a solar tracker one of the most effective methods for optimizing the efficiency of PV panels. By assisting PV panels in capturing more sunlight throughout the day, solar trackers enhance overall energy production. A solar tracker is a mechanical device that rotates PV panels to achieve an optimal angle concerning the sun's rays. The greater the perpendicular alignment with the sun's rays, the greater the efficiency of the PV panels. The two primary types of trackers are Single-axis and dual-axis solar trackers into which solar tracking systems can be separated based on their design and operation. The single axis of rotation used by single-axis solar trackers is used to align them with the sun. The axis of rotation of such trackers can be horizontal, vertical, or with a fixed angle of rotation, depending on the tracker location coordinates. In addition, Single-axis trackers offer simplicity and cost-effectiveness, while dual-axis trackers provide greater precision, albeit with higher implementation costs. Despite these challenges, solar trackers play a crucial role in maximizing solar radiation capture and improving the performance of photovoltaic installations (Tukymbekov et al., 2019; Saymbetov et al., 2021; Stefenon et al., 2021; Wu et al., 2022; Dixit et al., 2023).

II. PROBLEM STATEMENT

The project aims to design a model mechanism enabling a PV panel to effectively track a moving light source, maximizing energy capture. Additionally, the goal is to establish remote supervision and control of the prototype via the Arduino IoT cloud platform. To achieve this, several challenges need addressing, including:

- ❖ Determining how the PV panel can accurately track the position of the sun or light source.
- ❖ Ensuring the panel can be directed to point in specific directions as needed.
- ❖ Developing a platform for remote interference with the tracking system, including unlimited distance monitoring and control such as powering ON/OFF when necessary.
- ❖ Implementing mechanisms to measure various results, including physical quantities like light intensity, direction, PV pqnel voltage, tilt angle of the PV panel, and temperature, while ensuring the accuracy of the tracker.

II.1 Research Aim and Objectives

The project aims to develop an intelligent dual-axis sun tracking system with remote control capabilities to optimize solar PV panel efficiency. Utilizing the Arduino Internet of Things (IoT) cloud platform and a PC-based graphical user interface (dashboard), the system tracks light sources and measures various parameters. Users can easily control the system via a user-friendly dashboard interface without extensive Arduino programming knowledge. The main goal is to keep the solar PV panel perpendicular to the sun throughout the year for maximum efficiency. A literature study is conducted to explore the problem background and design a theoretical framework for the system further by implementing the system in reel life.

II.2 The specific objectives that guided this study are as follows:

The specific objectives of the study are as follows:

- ➢ Obtain an overview of the Arduino IoT cloud platform.
- ➢ Design and construct a dual tracking mechanism.
- ➢ Develop electronic hardware components to control the tracking mechanism using Arduino UNO microcontroller (ATmega328), Arduino IoT cloud, ESP32 module, servomotors, etc.
- ➢ Design, sketch, and implement intelligent dual-axis tracking and remote control code to automatically control the tracking components.
- ➢ Create a system suitable for other contexts requiring remote monitoring and control of solar tracker prototypes from unlimited distances.
- ➢ Explore existing software and hardware platforms relevant to the study.

III. ELECTRICAL EQUIVALENT MODEL OF A PV CELL

Figure. 1 presents the basic PV cell electrical model, known as the one-diode model. A current source, a diode, a shunt resistor, and a series resistor are its four fundamental parts. The current source, i_{ph}, represents the PV cell photon current formed from light. The diode, D, represents the p–n junction in the PV cell. The shunt resistance, R_{sh}, models leakage current in the PV cell. The series resistance, R_s, models internal and external resistances of the PV cell. PV cell output current and voltage are denoted as i_{pv} and v_{pv}, respectively. The PV cell's electrical model is used to electrically, or mathematically, describe and model its behavior.

The output current from the PV cell, i_{pv}, is expressed as Eq. (5) and corresponds to the output voltage, V_{pv} (Motahhir *et al.*, 2018):

$$i_{pv} = i_{ph} - i_s\left[e^{\frac{q(V_{pv}+R_s\, i_{pv})}{KTa}} - 1\right] - \frac{V_{pv} + R_s\, i_{pv}}{R_{sh}}$$

where i_s the diode reverse-bias saturation current, q is the electron charge (1.6×10^{-19} C), k is the Boltzmann constant (1.38×10^{-23} J/K), T is the PV cell temperature in Kelvins, and a is the diode ideality factor.

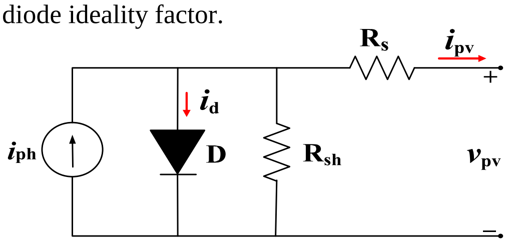


Figure 1: One-diode PV Cell model

To achieve the desired voltage and current levels, Ns cells are connected in series and Np cells are connected in parallel respectively, thus forming a PV module. While the PV module parameters are scaled according to Ns and Np as given below:

$i_{phM} = N_P X\ i_{ph}$

$i_{sM} = N_P X\ i_s$

$aM = N_s X\ a$

$R_{sM} = \frac{N_s}{N_p} X\ R_s$

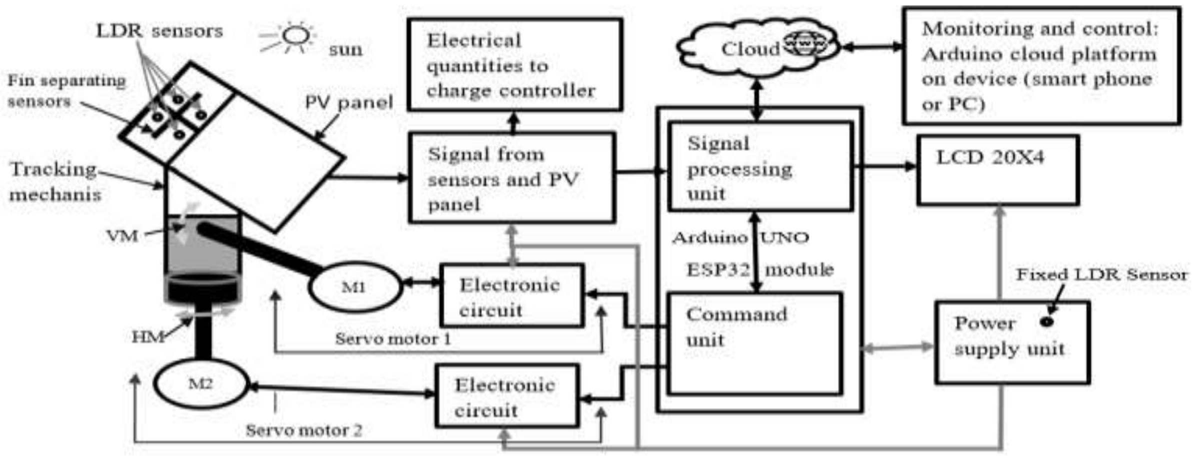
$R_{shM} = \frac{N_s}{N_p} X\ R_{sh}$

$$i_{pvM} = N_p i_{ph} - N_p i_s \left[e^{\frac{q\left(\frac{V_{pvM}}{N_S} + \frac{R_S\, i_{pvM}}{N_P}\right)}{KTa}} - 1 \right] - \frac{\frac{V_{pvM}}{N_S} + R_S\, i_{pvM}}{R_{sh}}$$

IV. Hardware Block Diagram Of The Intelligent Dual Axis Sun Tracker

IV.1 Background Theory

Solar (PV) monitoring system is widely used because monitoring and maintenance play key roles in solar power plants. A user of the system would typically want to know what his/her renewable energy system is generating, the amount of voltage, current, temperature, panel position, and light intensity readings at specific times of a day be it wire or wireless. In order to implement a successful monitoring and control system, devices known as sensors, MCU are need to be used. In this section presents the system design of the dual-axis Photovoltaic tracking system. The Monitoring and control of the tracker system for the proposed system is for tracking and monitoring solar photovoltaic using Arduino UNO (ATmega328 microcontroller) integrated directly into the current sensor, voltage sensor, temperature sensor, light sensors, power supply, servo motors, 4V monocrystalline PV panel. The schematic diagram below illustrates how the various components in the system communicate to move the PV panel to sun detected position and to also remotely monitor and control the tracker from the cloud platform via point access (Wi-Fi) at an unlimited distance.



SOURCE: KONEH Dulas Kului; modifies knowledge from, microprocessor, microcontroller, signal processing, and "Capteur et CEM GEL551" classes, applied with respect to how we want our dual axis tracker should operate.

Figure 2: Block diagram of an intelligent dual axis-tracking system.

V. Mathematical Modelling Of Pv Module In Matlab Simulink

Below is the complete structure of the PV module developed in matLab Simulink for simulation.

The output of a PV module is primarily influenced by temperature and solar irradiation. Temperature and irradiance changes cause variations in PV voltage and current. Under standard conditions, with an air mass of 1.5, irradiation of 1000 W/m2, and a temperature of 25°C, the PV module operates optimally.

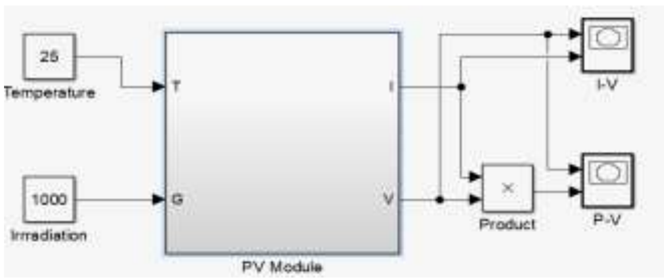


Figure 3: The simulation of the PV Module in Mat Lab Simulink

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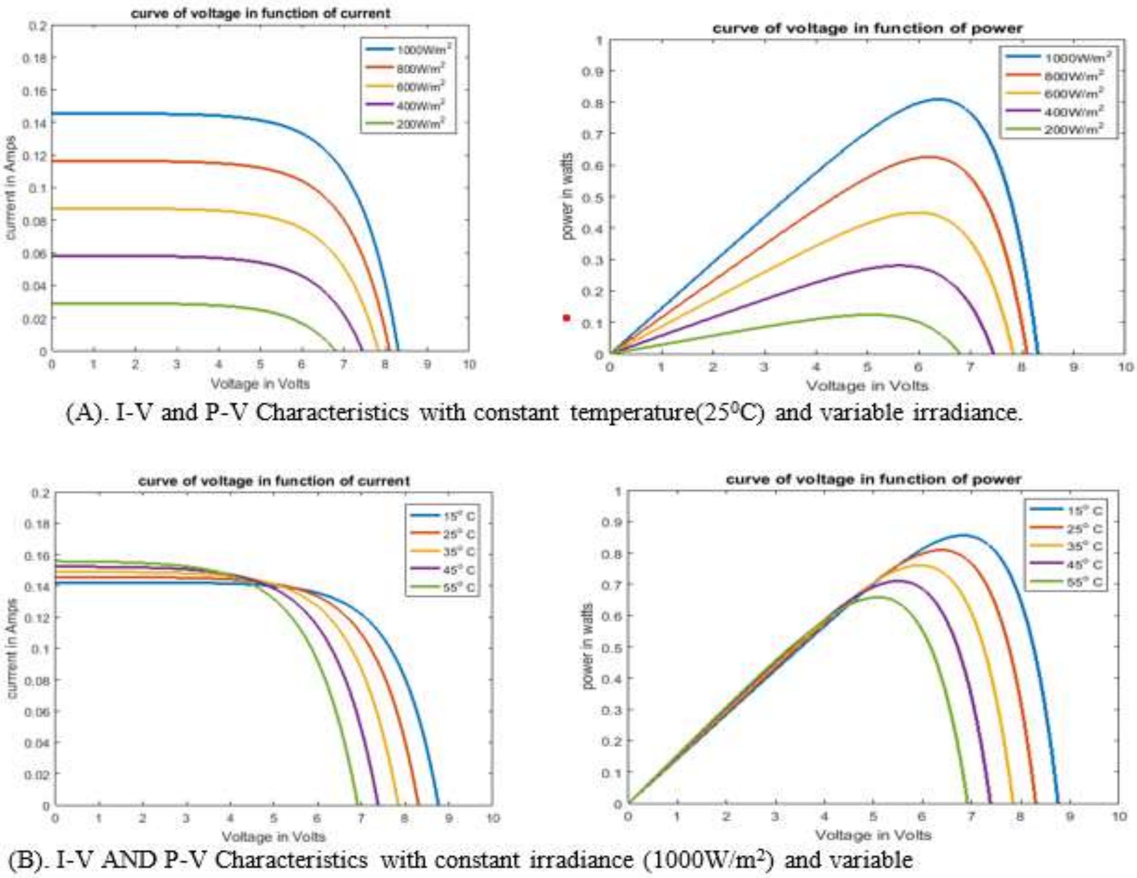

Figure 4: The effect of changes in solar irradiance and temperature on PV module characteristics

Figure 4 illustrates the impact of temperature and irradiance on the PV module's output. In Figure 4(A), the open-circuit voltage remains relatively constant, while variations in irradiance greatly affect the output current. Conversely, Figure 4(B) shows that changes in temperature lead to fluctuations in output voltage, while the short-circuit current remains relatively constant. This demonstrates how temperature and irradiance affect the PV module's output power, with decreasing irradiance leading to a drop in output power in Figure 4(A), and an increase in temperature causing a decrease in output power in Figure 4(B).

VI. Flowchart Of The Azimuth Angle Control

Azimuth is the angle of the object around the horizon, typically measured from true north and increasing eastward. The Light-Dependent Resistor North (LDRN) sensor is

installed facing north, while the Light-Dependent Resistor South (LDRS) sensor, installed facing south. The sensors are mounted on a movable part of the tracking mechanism to measure light intensity in both directions. This data is used to control servomotor_2 for horizontal tracking, enabling movement from north to south and vice versa, as well as for elevation tracking angle that controls the East to West movement (vertical movement).

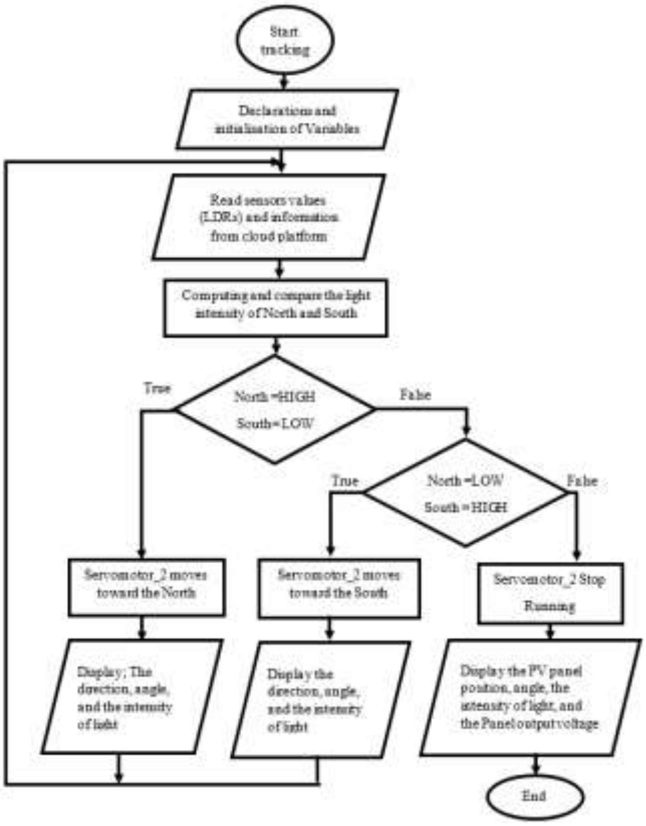

Figure 5: The Algorithm flowchart for tracking North and South movements.

VII. CIRCUIT DIAGRAM OF SUN TRACKING SYSTEM

The provided simulation schematic diagram, created and simulated in Proteus, preceded the implementation of the prototype, encompassing both software and hardware components. This schematic represents a smart dual axis sun tracking system designed to optimize the energy output of PV panels in different weather conditions.

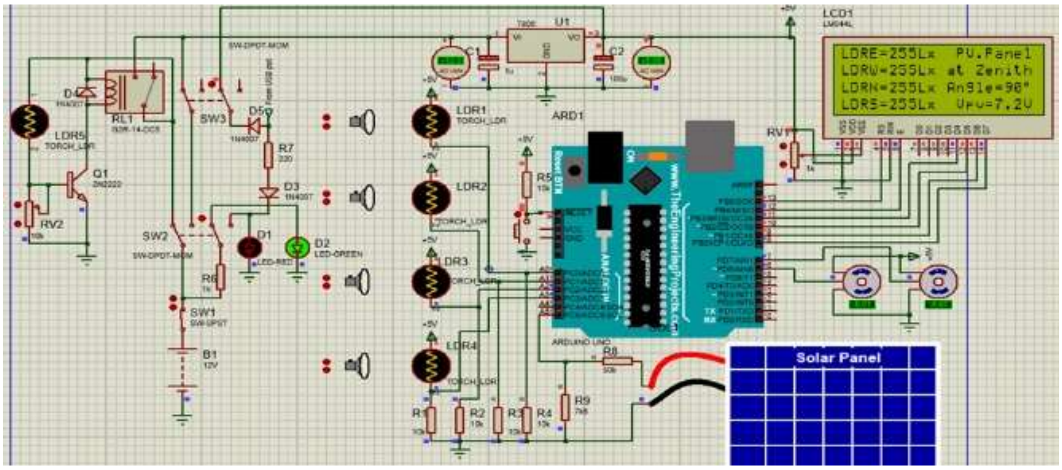

Figure 6: The simulation diagram of the intelligent dual axis sun tracking system

Where;
SW1: Is the power ON/OFF switch
SW2: Is the Mode selector switch.
SW3: Is the tracking switch.
D1: is a Red LED that detects maintenance mode.
D2: Is a Green LED that indicate the normal operating mode.

VIII. EXPERIMENTAL ASSESSMENT OF A FIXED PANEL SYSTEM AND AN INTELLIGENT DUAL AXIS SUN TRACKING SYSTEM

An intelligent sun tracker prototype has been successfully designed and implemented, operating with embedded logic to control individual system components. Utilizing servo-motors and LDR sensors controlled by an Arduino UNO which is connected with ESP32 board in 12C mode communication. That is, the ESP32 receive data from the Arduino card and forward to Arduino IOT cloud and vice versa, the solar panel tracks sunlight daily and seasonally, maintaining optimal angles. Additionally, the system allows for unlimited distance monitoring and control. Experimental data was collected on both cloudy and sunny days, showcasing the system's performance in different weather conditions. The experiments took place in Bini village, Obama City, Ngaoundere, with data recorded simultaneously from fixed and tracking panels.

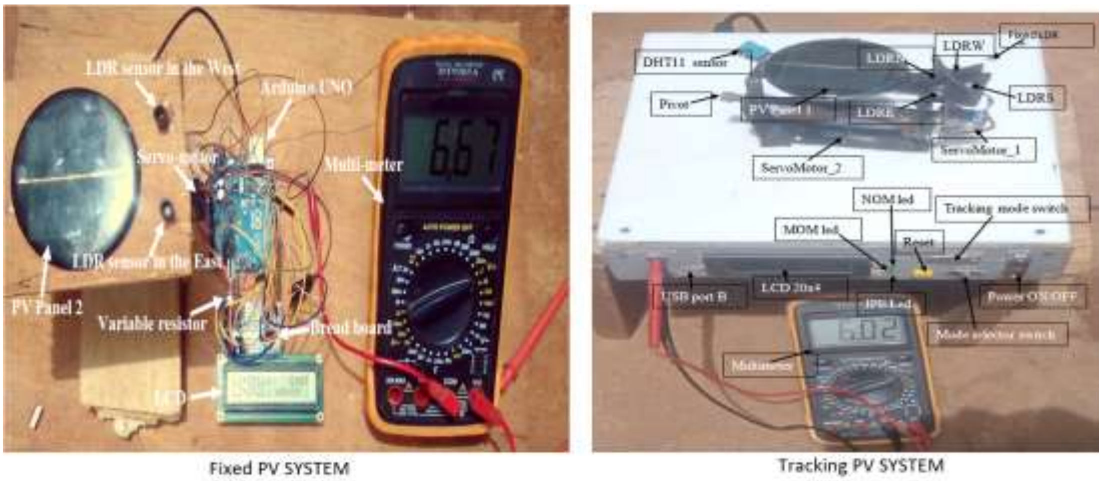

Figure 7: The photos of the fixed PV system and a dual axis tracking system

VIII.1 Experimental Setup for Data Acquisition

An IoT-based unlimited-distance remote system was developed for monitoring and controlling the intelligent dual axis solar tracking prototype using Arduino IoT (Internet of Things) Cloud. Experimental data, recorded wirelessly via Arduino IoT Cloud using an Android phone and a personal computer, was limited to five variables due to account restrictions (free account used). These variables included; a Graphical Power ON/OFF switch, Irradiation Monitor, Voltage

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ISSN (Online): 2455-9024

Monitor, Panel Position Monitor, and Temperature Monitor. Variations in irradiation, temperature, panel output voltage, and angles were observed from live graphs plotted in the graphical user interface (GUI) from the live readies of the prototype sensors values forwarded to IOT cloud. Initial irradiation increased rapidly when the PV panel was exposed to sunlight, followed by a decrease over time. Temperature gradually increased while panel output voltage slightly decreased. Monitoring and control of the prototype were demonstrated on an android phone and a personal computer dashboard, showing parameters such as panel angle, irradiation, panel output voltage, and temperature. The live graphs illustrated how these parameters varied with environmental conditions.

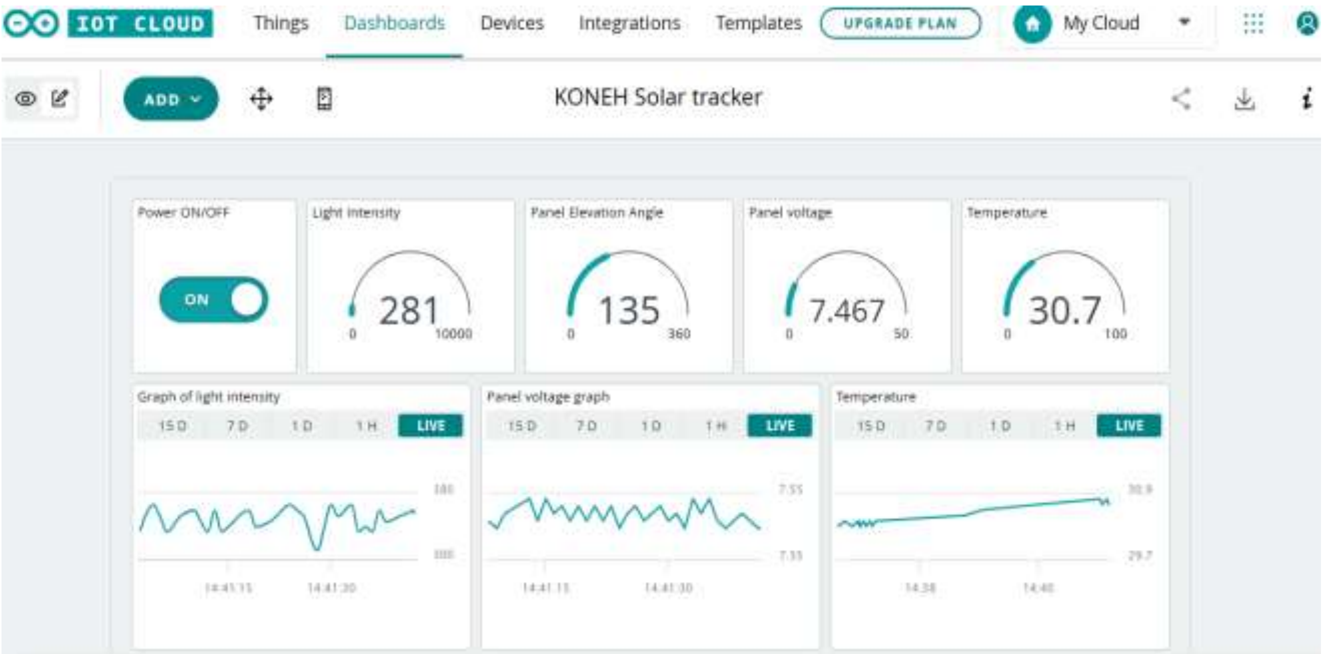

Figure 8: A screenshot of the wireless monitoring and control API recording data from the prototype is displayed on a personal computer, as well as on an Android phone.

Table 1: Characteristics of the Monocrystalline PV Modules use to carried out the experiment.

Parements	Values
Typical peak power (P_{mpp})	800mWc
Voltage at peak power (V_{mp})	4V
Current at peak power (I_{mp})	0.16A
Open-circuit voltage (V_{oc})	9V
Short-circuit current (I_{sc})	200mA
Series cells (N_s)	12
Parallel cell (N_p)	1
Load voltage	4V

VIII.2 presents data acquisition curves comparing a fixed panel system with the proposed dual-axis tracking panel.

Experimental data collection involved the tracking robot and fixed panel system on both a cloudy and sunny day. The experiments occurred on March 2nd, 2023, with a cloudy sky, and March 17th, 2023, with a clear sky. Data from both fixed and tracking panels, with identical characteristics, was recorded simultaneously. The experiments took place in Ngaoundere precisely Bini village at Obama city, situated at latitude 7.3°N and longitude 13.6°E.

The above curve shows the recorded produced power values of a 4V fixed PV panel system and that of a 4V tracking panel system with the same characteristics. The data for both panels were recorded synchronously at the same time on March 2nd, 2023. According to the graphs, it is evident that from 6:18 AM in the morning, the tracking panel was producing varying output power, which was higher than that of the fixed panel. Additionally, their values were closer by noon when the sun reached its zenith. We observed the maximum power output of the day from 11:18 AM to 12:17 PM for the fixed panel system and from 11:18 AM to 3:18 PM for the tracking panel.

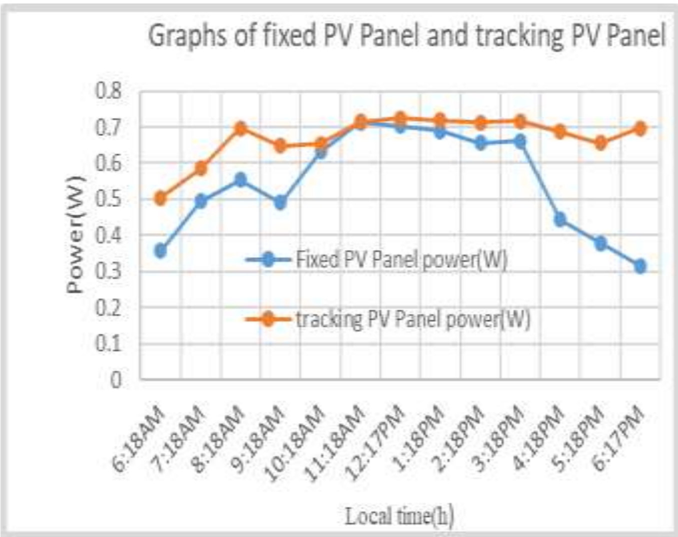

Figure 9: The graph of Power as a function of time of a 4V PV panel on a cloudy day March 2nd, 2023.

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VIII.2.1 The power energy gain in the proposed sun tracking system on March 2nd, 2023, a sunny day.

The power energy gains in the proposed sun tracking system on March 2nd, 2023, on a cloudy day are significant. We utilized the following formula to calculate and determine the power gain from our systems.

$$PPG = \frac{power\ with\ tracking\ pannel - power\ with\ fixed\ pannel}{power\ with\ tracking\ pannel} * 100$$

Where PPG is the Percentage power gain.

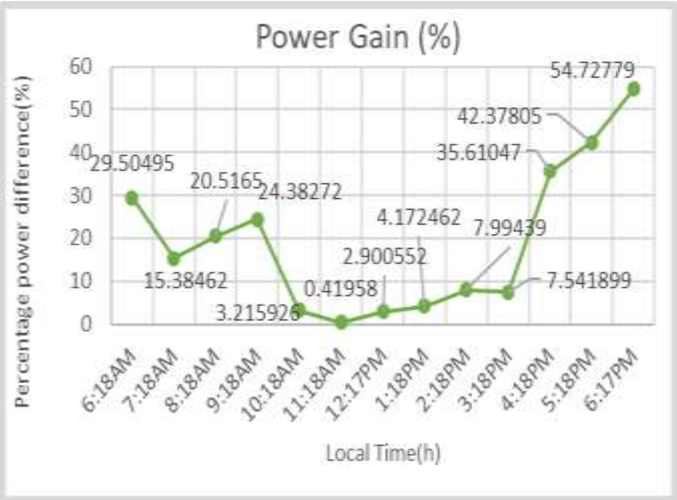

Figure 10: Percentage Power gain as a function of time curve of a 4V PV panel cloudy day March 2nd, 2023.

The characteristic graph in Figure 10 illustrates a power gain observed for each hour of sunlight. On March 2nd, 2023, the sun rose/raise at 6:18 AM, resulting in a recorded percentage power gain of approximately 29.50%. This increase was attributed to greater sunlight falling on the tracking panel compared to the fixed panel due to the sun's angle of incidence. The power gain gradually decreased towards noon, with peak sunlight intensity occurring between 7:18 AM and 9:18 AM before diminishing. At 11:18 AM, both the fixed and tracking panels exhibited nearly identical power outputs, indicating minimal differences. Despite the sky not being very bright, a maximum power gain of approximately 54.72% was observed when using tracking. Additionally, the power graph for the fixed PV system and dual-axis tracking PV system was derived from data recorded on Friday, March 17th, 2023, which was a cloudy day.

The graph in Figure 11 illustrates the power output of a 4V PV panel on a sunny day. In the morning, starting at 6:11 AM, the tracking panel outperformed the fixed panel, with their outputs nearly equalizing by noon when the sun reached its peak. The fixed panel system peaked in power output from 11:11 AM to 12:14 PM, while the tracking panel maintained high output from 10:11 AM to 4:11 PM. After noon, the fixed panel's output significantly declined compared to the tracking panel, attributed to the tracking panel's near-zero light ray incidence angle throughout the day.

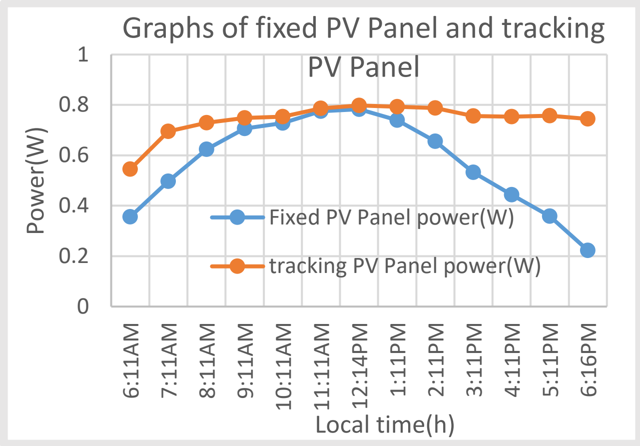

Figure 11: Graph of Power as a function of time of a 4V PV panel on a sunny day on March 17th, 2023.

VIII.2.2 The power energy gain in the proposed sun tracking system on March 17th, 2023, a sunny day.

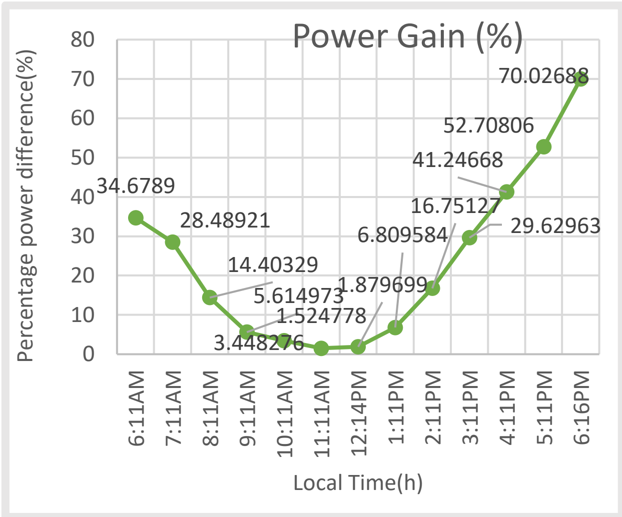

Figure 12: Percentage Power gain as a function of time curve of a 4V PV panel bright sunny day on March 17th, 2023.

The analysis of the characteristic curve in Figure 12 reveals that maximum sunlight typically occurs around midday, with peak values for the fixed panel occurring between 11:11AM and 12:14PM, and for the tracking panel between 10:00AM and 4:11PM. The tracking system is programmed to automatically switch off after sunset to conserve energy, reactivating at dawn when sufficient sunlight is available. Additionally, it can deactivate during dark periods and resume operation when the weather clears enough for adequate energy production. The tracking system demonstrates its highest efficiency during sunny conditions.

Comparing the power output of PV panels between tracking and fixed systems, it's clear that the tracking system yields increased power output. This is attributed to the dependency of PV panel power generation on light intensity, with higher intensity resulting in greater power generation. Notably, during the test period from November 2022 to March 2023 in Bini of Ngaoundere, the average solar irradiance was approximately

6kW/m^2. Analysis depicted in Figures 10 and 12 illustrates a significant percentage power gain of up to 54.72% and 70.02% on a cloudy day and a sunny day, respectively, when utilizing the solar tracker compared to fixed panels. Tchakounté et al. (2019) conducted a study on a single-axis tracker in Bini of Ngaoundere, highlighting energy gains of 22.45% and 24.86% for cloudy and sunny days, respectively, with a medium-sized panel. It's acknowledged that the percentage power gain may vary with panel size and accuracy of the tracker. Their system, however, is limited to single-axis tracking and lacks distance monitoring and control features present in our prototype.

IX. Problems Resolved By Our Prototype

The team has developed and implemented an intelligent dual-axis sun-tracking system, which successfully addressed several scientific problems in the field of photovoltaic energy systems. The system optimizes the energy production of photovoltaic panels, manages stored energy using artificial intelligence, and reduces power consumption. It also includes automatic switching from dual-axis to single-axis tracking, based on the sun trajectory of the day, thereby reducing the tracking load and extending the system's lifespan. The system operates in deep sleep mode with lower power consumption, conserving stored energy and extending the system's lifespan. Additionally, remote monitoring and control of the tracker from unlimited distances also help reduce operating time, thereby increasing the system's lifespan.

X. Conclusion

The global demand for energy is depleting natural resources rapidly, prompting a shift towards renewable energy solutions to address the looming energy crisis. Solar energy, in particular, is gaining traction as a crucial renewable energy source. However, the efficiency of solar PV panels remains a significant concern, especially considering that many installations remain fixed throughout the day, resulting in decreased efficiency. To address this issue, we developed an intelligent dual-axis sun tracking system capable of maximizing solar energy capture by following the sun's trajectory throughout the day. Solar PV energy offers widespread acceptance and is seen as a reliable, environmentally friendly, and intelligent alternative to traditional electricity-generating sources. Our tracking mechanism significantly improves energy production compared to fixed panel installations, with experimental tests demonstrating power gains of up to 54.72% on a cloudy day and 70.02% on a brighter day.

Perspective:

In the future, the prototype will undergo further mechanical enhancements to facilitate large-scale implementation. These upgrades will include features such as automatic panel cleaning (self-cleaning), a cooling system, and wind protection to optimize performance and durability.

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