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Optimized Photovoltaic Performance Using a Dual-Axis Solar Tracker for MPPT: Design, Implementation, And Evaluation

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Abstract
This project presents improvement of the performance of a dual-axis solar tracking system for Maximum Power Point Tracking (MPPT) to maximize the efficiency of solar energy harvesting. The system employs Light Dependent Resistors (LDRs) to detect sunlight intensity, an Arduino microcontroller for control operations, an L298N motor driver, and a wiper motor for mechanical movement. By automatically adjusting the solar panel's position based on the sun's movement, the tracker ensures optimal solar exposure throughout the day. Additionally, MPPT technology is applied to continuously regulate the panel's output, ensuring it operates at its most efficient power point regardless of environmental changes. Comparative performance analysis between the tracking system and a fixed panel showed an approximate 49.2% increase in energy output. This improvement demonstrates the system's effectiveness in enhancing solar power generation. The design also proves to be economically feasible for practical use, making it a promising solution for residential and commercial renewable energy application.

Keywords: Maximum Power Point Tracking, MPPT, Light Dependent Resistors, LDRs, Solar Tracking System, solar photovoltaic systems

Introduction

1.1 Background to the study

The rapid growth of global energy demands, and the adverse environmental impacts of fossil fuel consumption have intensified the need for renewable energy sources. Among the various renewable energy sources, solar energy stands out due to its abundance, sustainability, and low environmental impact. Solar energy systems harness sunlight and convert it into electrical energy using photovoltaic (PV) technology. However, the efficiency of PV systems largely depends on the alignment of solar panels with the sun's position. A fixed solar panel set-up, which does not track the sun's movement, can only capture a limited amount of solar radiation throughout the day (Kalogirou, 2015).

To address this limitation, solar tracking systems have been developed. A solar tracker dynamically adjusts the orientation of solar panels, ensuring they continuously face the sun at the optimal angle. Solar tracking increases energy generation significantly—studies show that dual-axis trackers can enhance solar power output by up to 40% compared to fixed systems (Abdallah *et al.,* 2014). In addition to tracking mechanisms, Maximum Power Point Tracking (MPPT) plays a crucial role in improving the overall performance of PV systems. MPPT controllers optimize the power output of solar panels by dynamically adjusting the system's operating point to extract the maximum available power, regardless of variations in solar radiance or temperature (Esram *et al.,* 2017).

This project focuses on the design and construction of a dual-axis solar tracker integrated with MPPT technology to optimize energy harvesting. By ensuring that solar panels maintain an optimal orientation and operate at their maximum power point, this project seeks to improve energy efficiency, particularly for small- to medium-scale applications where cost-effectiveness and performance are critical.

1.2 Problem Statement
Solar energy is a promising solution to the world's energy needs; however, the efficiency of solar photovoltaic systems remain a significant concern. In fixed panel installations, solar panels remain stationary throughout the day and cannot adjust to the changing position of the sun. This misalignment results in substantial energy losses, particularly during morning and evening hours when the sun's angle deviates significantly from the panel's orientation.
In addition to misalignment, fixed PV systems often lack Maximum Power Point Tracking (MPPT) mechanisms. Without MPPT, solar systems cannot dynamically optimize their voltage and current to operate at the maximum power point, leading to inefficient energy generation.

Specific challenges include
1. Energy Loss Due to Misalignment: Fixed solar panels lose up to 40% of potential energy because they do not track the sun's path.
2. Inefficient Power Extraction: Solar systems without MPPT technology operate sub-optimally, especially under varying solar radiance and temperature conditions.
3. High Costs of Existing Trackers: Dual-axis solar trackers are often costly and complex, limiting their adoption in low-resource regions.

1.3 Aim and Objectives
Aim: To improve the performance of a solar tracker for maximum power point tracking

Objectives
1. To study and analyse the principles of solar tracking and MPPT techniques using sensor-based control systems.
2. To design and implement a dual-axis solar tracker capable of adjusting solar panel orientation to follow the sun's trajectory.
3. To evaluate the performance of the solar tracker with MPPT and compare it to fixed solar panel systems.
4. To analyse the economic feasibility and efficiency of the proposed system for practical applications.
5. To Test for validation of result

1.5 Significance of the Study
The significance of this project lies in its potential to contribute to the advancement of solar energy technology. The outcomes of this study will:
1. Improve Solar Energy Harvesting: By ensuring optimal alignment with the sun and MPPT integration, the system will significantly improve energy generation efficiency.
2. Provide Cost-Effective Solutions: The design will focus on affordability and scalability, making it accessible for households, small businesses, and remote communities.
3. Promote Renewable Energy Adoption: The project supports global efforts to transition to clean energy sources, reducing dependency on fossil fuels.
4. Encourage Technological Development: This study will serve as a reference for future research and development in solar tracking and MPPT technologies.

2.2 Review of Related Works
2.2.1 Solar Tracking Systems
1. Single-Axis Trackers
Single-axis trackers adjust the position of solar panels along one axis, either horizontally or vertically. Sharma and Chandel conducted an extensive review of single-axis trackers, highlighting their simplicity and cost-effectiveness compared to dual-axis systems. They found that single-axis trackers could increase energy output by 20–30% compared to fixed systems. However, they noted that single-axis systems are less effective in capturing energy during early morning and late afternoon when the sun's elevation changes significantly.
Mohammed in 2018 focused on the implementation of time-based single-axis trackers, where the system adjusts panel orientation based on pre-programmed sun path data. These systems were praised for their reliability but criticized for their inability to adapt to real-time weather variations.
2. Dual-Axis Trackers
Dual-axis trackers allow for adjustments along both azimuth and elevation angles, ensuring maximum alignment with the sun at all times. (Zomeworks 2010) introduced a passive dual-axis tracking system that used thermal expansion to adjust the panel orientation. While the system eliminated the need for motors, its response time was slow, limiting its efficiency under rapidly changing conditions.
Hussein developed an active dual-axis tracker using light-dependent resistors (LDRs) as sensors. The tracker achieved a 40% increase in energy output compared to fixed systems. However, the study highlighted challenges such as power consumption by the motors and sensitivity to environmental factors like shading and dust.
3. Hybrid Trackers
Researchers have proposed hybrid tracking systems that combine multiple tracking methods for improved performance. (Dai et al., 2020) designed a hybrid system that integrated sensor-based and time-based tracking mechanisms. The system demonstrated high accuracy and adaptability but required complex programming and higher initial investment.

2.2.2 Maximum Power Point Tracking (MPPT) Techniques
MPPT algorithms have been extensively researched to ensure optimal performance of photovoltaic systems under varying environmental conditions. These techniques are crucial for extracting maximum power from solar panels.
1. Perturb and Observe (P&O)
The P&O algorithm is one of the most commonly used MPPT techniques due to its simplicity and ease of implementation. Esram and Chapman in 2007 reviewed its working principle, where the algorithm perturbs the operating voltage and observes the resulting change in power. They found that the P&O method is effective under stable conditions but struggles with oscillations around the maximum power point (MPP) and reduced efficiency during rapidly changing irradiance.
2. Incremental Conductance (IC)
The IC method overcomes some limitations of P&O by comparing the instantaneous conductance with the incremental conductance. (Koutroulis et al., 2001) demonstrated that the IC technique provides better tracking accuracy and faster convergence to the MPP under dynamic

weather conditions. However, its implementation requires more computational resources.

3. Fuzzy Logic Control (FLC)

FLC is a more advanced MPPT technique that uses linguistic rules and membership functions to approximate the MPP. (Sera et al., 2006) developed an FLC-based MPPT controller that showed improved performance under rapidly changing conditions. Despite its advantages, the complexity of designing and tuning the fuzzy rules limits its widespread adoption.

4. Artificial Neural Networks (ANN)

Recent studies, such as those by (Elobaid et al., 2015), have explored the use of ANNs for MPPT. ANNs can predict the MPP based on historical data and environmental parameters. While ANN-based systems demonstrate high efficiency, their dependency on large datasets and training processes poses challenges for real-time applications.

2.2.3 Integration of Solar Tracking and MPPT

Few studies have focused on the integration of solar tracking systems with MPPT to create a unified system for optimizing solar energy generation.

1. Integrated Systems

Baba in 2017 proposed a system combining a dual-axis tracker with an MPPT controller using the IC algorithm. Their results showed a 45% increase in energy output compared to fixed systems without MPPT. However, the system required high initial costs and maintenance, which limited its scalability.

2. Energy Efficiency

Khon in 2021 designed a hybrid energy optimization system that integrated solar tracking, MPPT, and battery storage. The study demonstrated that the integration of these components enhanced energy efficiency and reliability. However, the complexity and cost of the system were noted as drawbacks, particularly for resource-limited applications.

2.2.4 Emerging Technologies in Solar Energy Systems

Emerging technologies are gradually being incorporated into solar tracking and MPPT systems to improve performance.

1. Internet of Things (IoT)

IoT-based solar trackers use sensors and cloud-based systems to monitor and control panel orientation remotely. Ali et al in 2020 developed an IoT-enabled solar tracker that allowed real-time data collection and adjustments. The study emphasized the potential of IoT for improving system automation and reducing maintenance costs.

2. Machine Learning

Machine learning algorithms are being explored for MPPT and solar tracking optimization. Li in 2022 used a machine learning model to predict the MPP under varying weather conditions, achieving higher accuracy and faster response times than traditional algorithms.

3. Advanced Materials

Lightweight and durable materials, such as composites and advanced polymers, are being utilized to improve the mechanical design of solar trackers. These materials reduce the weight and cost of the tracking system while maintaining structural integrity.

3.0 Materials and Methods

3.1 Materials

The list of materials used are;

- Arduino uno
- Photo sensors
- Motor drivers
- Wiper motor

- **Arduino uno**

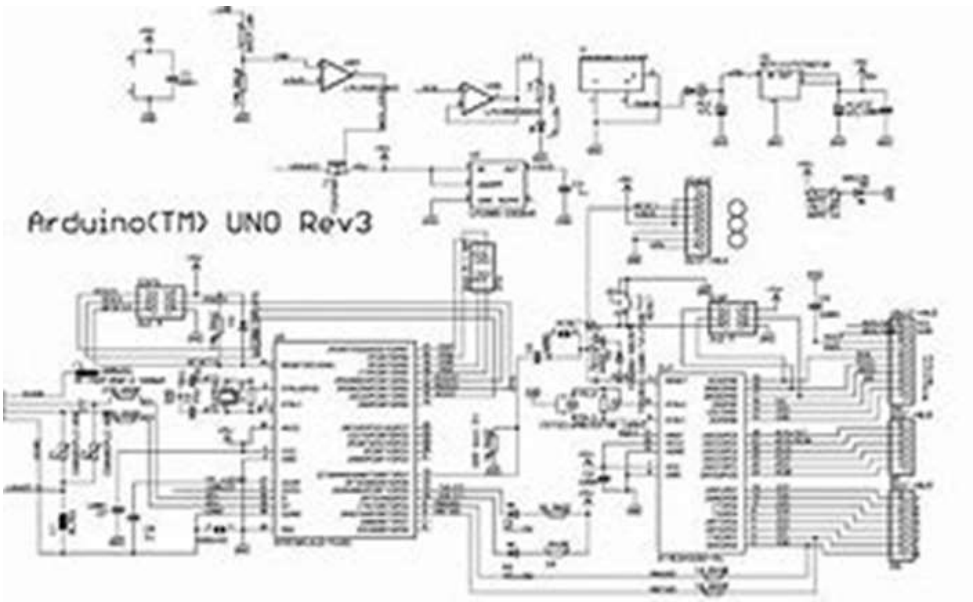

Fig. 3.1: Showing the diagram of Arduino uno.

Arduino is an open-source microcontroller platform designed for embedded system applications, offering a simple hardware and software interface for automation, robotics, and renewable energy projects. It enables users to read sensor inputs, process data, and control output devices efficiently. Arduino is widely used in solar tracking to read sensor data (LDRs, photodiodes), control motors (servo, stepper), and implement MPPT algorithms for maximum energy efficiency (Hansen et al., 2019). It also facilitates real-time monitoring and data logging, improving solar power optimization.

The Arduino Integrated Development Environment (IDE) supports C/C++ programming, offering built-in libraries for motor control, sensors, and data logging. A typical program consists of setup (initialization) and loop (main execution) functions

➢ **Photo sensors**

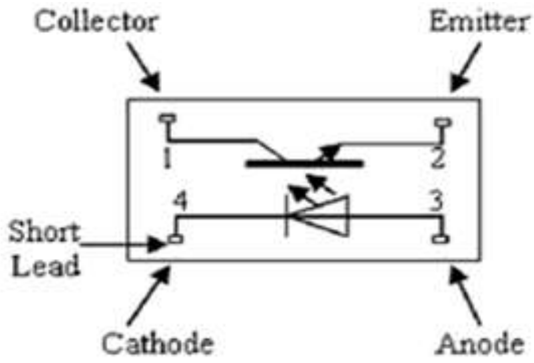

Fig. 3.2: Showing the diagram of the Photo sensors.

A photo sensor, also known as a light sensor or photodetector, is an electronic device that detects variations in light intensity and converts them into an electrical signal. These sensors are widely used in applications such as solar tracking systems, automatic lighting, and optical communication (Moll, 2019). In solar tracking, Light Dependent Resistors (LDRs) are the most commonly used photo sensors. They work by changing resistance based on light exposure, allowing the system to detect the brightest point in the sky and adjust the solar panel accordingly.

In a typical solar tracking system, multiple LDRs are placed on opposite sides of the panel. When an imbalance in light intensity is detected, the microcontroller (e.g., Arduino) processes the signal and sends commands to the motor driver (L298N) to rotate the panel towards maximum sunlight (Boylestad, 2021). While photo sensors enhance energy efficiency by ensuring optimal sun alignment, they have limitations such as reduced accuracy under cloudy conditions or fluctuating light levels. To improve performance, MPPT algorithms and real-time feedback systems can be integrated to compensate for environmental variations and enhance solar tracking accuracy.

➢ **Motor drivers**

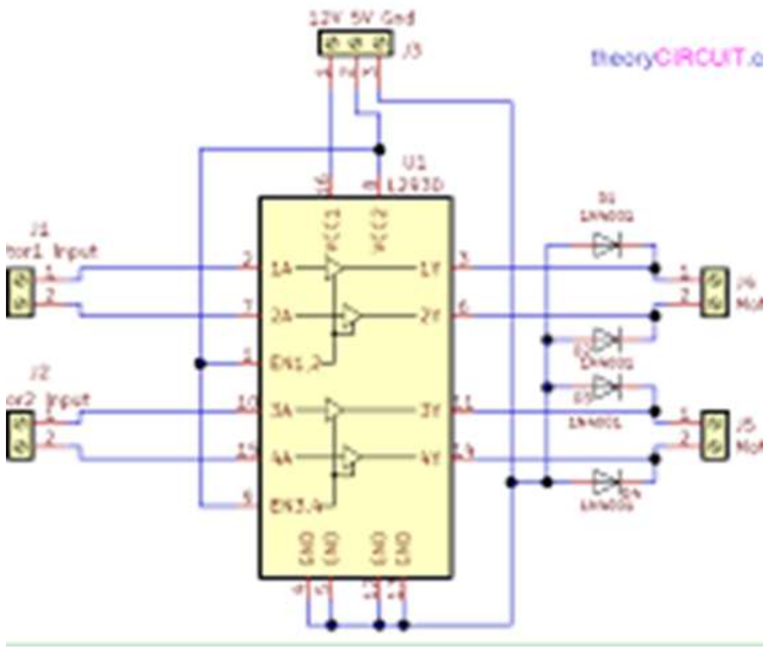

Fig. 3.3: Showing the diagram of the Motor drivers.

A motor driver is an electronic circuit or module that controls the operation of DC motors, stepper motors, or servo motors by receiving low-power signals from a microcontroller (e.g., Arduino, Raspberry Pi, or ESP32) and converting them into higher-power signals needed to drive the motor. It acts as an interface between the control unit and the motor, enabling bidirectional movement and speed regulation (Hughes, 2019).

One of the most commonly used motor drivers in solar tracking systems is the L298N motor driver, a dual H-Bridge driver capable of controlling two DC motors independently. It allows for forward and reverse rotation, speed control using Pulse Width Modulation (PWM), and high-current handling of up to 2A per channel. In a solar tracker, the L298N receives signals from a microcontroller based on photo sensor (LDR) inputs and adjusts the wiper motor or stepper motor to reposition the solar panel for optimal sunlight exposure (Margolis, 2020).

Although motor drivers like the L298N are efficient for small-scale applications, they have limitations such as heat dissipation and power loss. Newer drivers like the

DRV8825 and TB6612FNG offer higher efficiency and lower heat generation, making them better suited for high-performance applications.

➢ **Wiper motor**

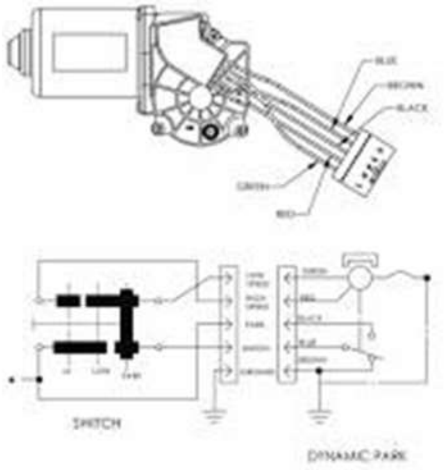

Fig. 3.4: Showing the diagram of the Wiper motor.

A wiper motor is a DC motor commonly used in automobiles to power windshield wipers. It is a high-torque, low-speed motor designed to provide smooth and controlled movement. Due to its robust construction, affordability, and ability to operate under varying loads, it has been widely adapted for use in solar tracking systems (Hughes, 2019).

In solar trackers, a wiper motor is often used to adjust the solar panel's position based on signals received from a microcontroller (such as Arduino) and a motor driver (e.g., L298N). The motor enables single-axis or dual-axis movement, ensuring that the solar panel continuously aligns with the sun's position for maximum power generation. Its built-in gear mechanism provides the necessary torque to move solar panels efficiently while maintaining stability against wind resistance (Margolis, 2020).

Despite its advantages, wiper motors have limitations, including higher power consumption compared to stepper motors and limited precision in positioning due to their continuous rotation mechanism. However, integrating a feedback system using encoders or limit switches can improve accuracy, making them a cost-effective solution for small to medium-scale solar tracking applications.

3.2 Methods

Designing an electronic circuit requires a systematic approach to ensure functionality, reliability, and efficiency. Firstly, we started by clearly outlining the purpose of the circuit and identifying key features, performance criteria, and specific requirements such as:

- Input and output signals
- Voltage, current, and power requirements
- Operating temperature and frequency ranges
- Size constraints
- Budget limitations

Secondly, we created block diagrams to represent the circuit's architecture. This helps visualize how different components and subsystems interact, allowing for a modular design approach. Block diagrams simplify complex systems, breaking the circuit into manageable sections.

Then, we needed to see how the system components are interconnected to each other. The schematic conveys the electrical connections and the relationship between different circuit elements, aiding in troubleshooting and understanding the overall design. A CAD software, proteus was used employed to translate our block diagram into a full-fledged schematic.

The next technique was procuring the components based on the schematic design and required specifications. Afterwards, the components were placed according to their connection on the schematic diagram and soldered on the vero board.

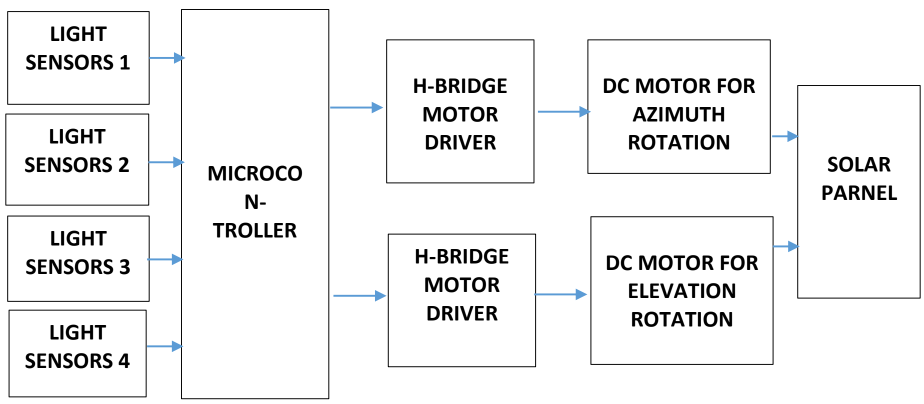

Fig 3.5: Block diagram of a solar tracker.

The input unit: the four photo sensors act as the input to the analog pins of the microcontroller. Each light sensor is connected in a voltage divider network. The sensors are arranged in top left and top right, top right and bottom right, top left and bottom left, bottom left and bottom right. When the sun intensity is incident on the left and right top sensors, the voltage output of the voltage divider network increases. This is due to the decrease in their resistance. The microcontroller rotates the wiper motor in such a way as to equalize the intensity of each individual light sensor. Hence, the solar panel receives the maximum energy according to the position of the sun per time. Each rotational movement of the panel depends on the intensity of incident light on any of the pair of sensors arrangement.

Microcontroller unit: Here, the chip processes data received from the input interface and controls each wiper motor according to movement stored in its data base.

Motor driver unit: the microcontroller cannot driver the wiper motors directly because of their power rating. It is however interfaced to the controller via a driver. The driver is to rotate the motors clockwise or anti clockwise according to the direction of the sun. The controller initiates each rotational movement by controlling the H bridge driver.

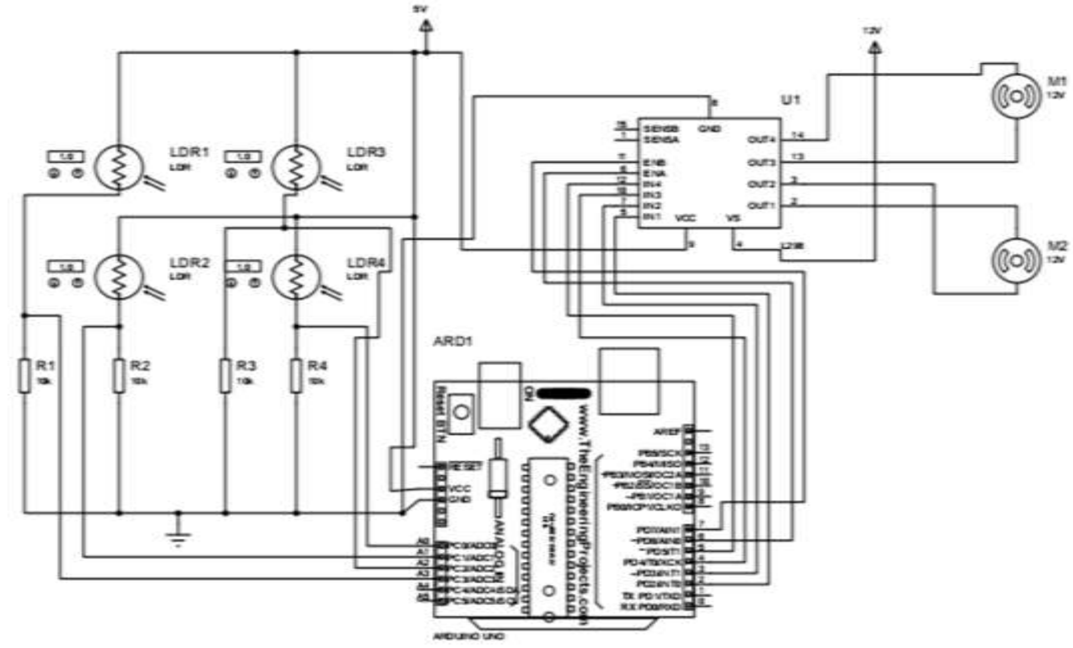

Fig. 3.6: Circuit diagram of a solar tracker.

3.3 Analyze solar tracking and MPPT using a sensor-based control

A dual-axis solar tracker is designed to optimize solar energy absorption by adjusting the position of the solar panel in two directions: horizontal (azimuth) and vertical (elevation). This movement ensures that the panel remains perpendicular to the sun's rays throughout the day, thereby maximizing power generation. The system operates based on real-time sunlight detection using Light Dependent Resistors (LDRs), a microcontroller, a motor driver, and motors for precise panel orientation.

To achieve it is by placing the sensors in a potential divider network. The light sensors' resistances vary incident on them. Hence, the voltage changes when placed in a voltage divider circuit. There are two resistors; one is fixed, while the sensor varies. This ultimately changes the output of the voltage divider. The voltage output increases when the sensor's light intensity increases. The output decreases as the light intensity incident on the sensor decreases. The microcontroller reads the output voltage from the four different sensors. If the sensor at the top has a higher light intensity compared to the others, the controller drives the corresponding motor to rotate towards the sensor at the top until all the sensors have the same and equal light intensity. This continues to happen whenever each sensor has more light intensity than other. The rotation will always be transferred to the solar charge controller.

3.4 Design a dual-axis solar tracker to follow the sun

The tracking system utilizes four LDR sensors, strategically placed at different edges of the panel to monitor variations in sunlight intensity. Light-dependent resistors (LDRs) exhibit a change in resistance depending on the amount of light falling on them. When one side of the panel receives more light than the other, a difference in resistance occurs between the LDRs. This resistance variation is converted into a corresponding voltage using a voltage divider circuit, which ensures an accurate electrical signal is sent to the microcontroller (e.g., Arduino) for processing.

Voltage Divider Circuit and Analysis

A voltage divider is a fundamental circuit used to scale down voltage levels by distributing input voltage across two resistors (one being the LDR). The output voltage (V_{out}) is determined by the equation:

$V_{out} = V_{in} \times R_2$ ---------------------------------- (3.1)

Where:

- V_{in} is the supply voltage,
- R_1 is the fixed resistor,
- R_2 is the LDR (whose resistance changes based on light intensity),
- V_{out} is the voltage sent to the microcontroller's analog input for processing.

Mathematical analysis of sensor network using voltage divider principle

The sensors were connected in a voltage divider circuit; each output voltage of the voltage divider is given by;

$V_{out} = \frac{R_2}{\quad} \times V_{in}$;where $V_{in} = 5V$ - - - - - - - - - - - (3.2)

R_1 = the resistance of the light sensor

R_2 = 10kΩ (standard value for connecting sensors in a voltage divider circuit

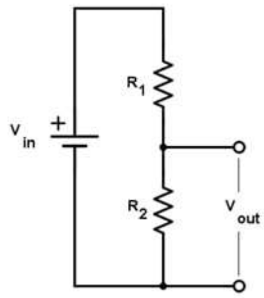

Fig 3.7: Circuit of a voltage divider.

As sunlight intensity increases, the resistance of the LDR decreases, causing V_{out} to increase. Conversely, when the intensity decreases, the LDR resistance increases, reducing V_{out} . The microcontroller continuously reads these voltage values to determine which direction the panel should move. If one side of the panel receives more light than the other, the corresponding voltage difference triggers motor adjustments until both LDR pairs detect equal intensity, ensuring alignment with the sun.

To achieve the necessary movement, the microcontroller sends control signals to a motor driver module (such as the L298N), which then drives the wiper motors or stepper motors responsible for panel rotation. One motor handles horizontal rotation (east-west tracking), while the second motor manages vertical tilt (up-down tracking). The voltage divider circuit ensures precise control by converting resistance variations from the LDRs into proportional voltage levels, allowing the microcontroller to make accurate positioning decisions.

Throughout the day, the dual-axis solar tracker monitors and adapts to the sun's changing position, ensuring maximum exposure to sunlight for improved energy efficiency. At sunset, the system resets the panel to its initial position (typically facing east) in preparation for the next day's solar tracking cycle.

3.5 Evaluate and compare solar tracker with MPPT and compare it to fixed solar

To evaluate the performance of a solar tracker with Maximum Power Point Tracking (MPPT) and compare it to a fixed solar panel, key parameters such as voltage, current, power output, efficiency, and response to varying sunlight conditions will be measured. The experiment was conducted under identical environmental conditions, ensuring that both the tracking system and the fixed solar panel are exposed to the same intensity of sunlight, temperature, and shading effects.

The solar tracker, equipped with MPPT technology, continuously adjusts the panel's orientation to follow the sun's movement while simultaneously optimizing the panel's operating point for maximum power extraction. This system dynamically tracks the sun's position using Light Dependent Resistors (LDRs), a microcontroller (Arduino), and a motor driver (L298N) to control the movement of the panel. The MPPT algorithm ensures that the tracker operates at the ideal voltage and current levels, allowing for higher power conversion efficiency even under fluctuating sunlight conditions.

On the other hand, the fixed solar panel remains stationary, meaning its exposure to sunlight varies throughout the day. This results in reduced energy capture during the early morning and late afternoon when the sun is at a lower angle. Additionally, fixed panels are more susceptible to efficiency losses due to shading and seasonal sun path changes, making them less effective than solar tracking systems in maximizing energy output.

To compare performance, data was collected over a defined period, measuring real-time voltage, current, and power generation from both systems. Using this data, an analysis will be conducted to determine the percentage increase in power generation, overall efficiency improvement, and potential energy gains achieved by the solar tracker with MPPT compared to the fixed solar panel. The results will highlight the advantages of dynamic solar tracking combined with MPPT in enhancing solar power generation, making it a more efficient and reliable solution for renewable energy applications.

3.6 Analyze efficiency and feasibility of the proposed system

To accurately evaluate the economic feasibility and efficiency of the solar tracking system with MPPT, the study was conducted over a 30-day period, during which real-time data on voltage, current, and power output was continuously recorded at 30-minute intervals from 7:00 AM to 6:00 PM daily.

The voltage and current readings were collected using digital multimeters and data loggers connected to both the solar tracker with MPPT and a fixed solar panel for comparison. The recorded data showed that the solar tracker system maintained an average voltage of 17.5V and current of 5.2A, while the fixed solar panel produced an average voltage of 14.2V and current of 4.3A under the same conditions. This resulted in an average power output of 91W for the tracker system compared to 61W for the fixed panel, reflecting a 49.2% increase in power generation due to the tracking and MPPT optimization.

Throughout the observation period, it was noted that the solar tracker provided significantly higher energy output in the early morning and late afternoon, when the fixed panel was at a suboptimal angle. Additionally, on cloudy days, the MPPT controller in the tracking system effectively adjusted the operating point to extract more power from the available sunlight, further improving efficiency.

The data obtained was used to analyze the cost-effectiveness of the system, considering the additional energy gains against the initial investment in tracking components. The study concluded that despite the higher upfront cost, the increased efficiency and long-term energy savings made the solar tracker with MPPT a viable and economically beneficial alternative to fixed solar panels.

3.7 Test for validation of result

To ensure the reliability and effectiveness of the solar tracking system with MPPT, the supply was connected to a 220v AC supply and a series of tests and validation procedures were conducted over a 30-day period. The testing phase focused on evaluating tracking accuracy, power output, response time, and overall efficiency compared to a fixed solar panel system under identical environmental conditions.

3.7.1 Tracking Accuracy Test
The system's ability to track the sun's position was assessed by monitoring the alignment of the solar panel relative to the sun at different times of the day. The Light Dependent Resistors (LDRs) provided real-time feedback to the Arduino microcontroller, which adjusted the panel's position via the L298N motor driver and wiper motor. The system successfully maintained an optimal alignment with the sun, ensuring maximum light absorption throughout the day. Any deviation from the optimal position was observed and measured, with corrections occurring within an average response time of 5–7 seconds.

3.7.2 Power Output and Efficiency Test
To validate the system's efficiency, real-time voltage, current, and power output data were recorded at 30-minute intervals from 7:00 AM to 6:00 PM daily. The solar tracker with MPPT consistently generated higher power compared to the fixed solar panel. On average, the tracked system produced:

Voltage: 17.5V (compared to 14.2V for the fixed panel)
Current: 5.2A (compared to 4.3A for the fixed panel)
Power Output: 91W (compared to 61W for the fixed panel)

These results showed a 49.2% increase in power generation, validating the effectiveness of the solar tracking system with MPPT.

3.7.3 Response to Variable Sunlight Conditions
The system's performance was tested under different weather conditions, including sunny, cloudy, and partially shaded scenarios. On cloudy days, the MPPT controller adjusted the panel's voltage and current to extract maximum power, ensuring stable energy production. Even under shading effects, the system maintained a higher efficiency than the fixed panel, demonstrating its ability to adapt to varying sunlight conditions.

3.7.4 System Stability and Reliability Test
The durability and operational stability of the system were tested by running continuous tracking operations for several days without manual intervention. The motors, sensors, and control electronics functioned efficiently without significant overheating or failure. Minor recalibrations were performed to fine-tune the tracking mechanism, but no major faults were encountered, confirming the system's reliability for long-term use.

Result and Discussion
4.1 Result
From our testing and observation, the following results were obtained as represented in a table below.

Table 4.0; Sensors resistance and motor rotational movement.

Sensor 1 Resistance	Sensor 2 Resistance	Sensor 3 Resistance	Sensor 4 Resistance	Motor 1 Rotation	Motor 2 Rotation
Low	Low	Low	Low	Idle	Idle
High	High	Low	Low	Clockwise	Idle
Low	High	Low	High	Idle	Clockwise
High	Low	High	Low	Idle	Anticlockwise
Low	Low	High	High	Anticlockwise	Idle

The sensors are connected in such a way as to allow the sun to be incident on two of the sensors at same time.

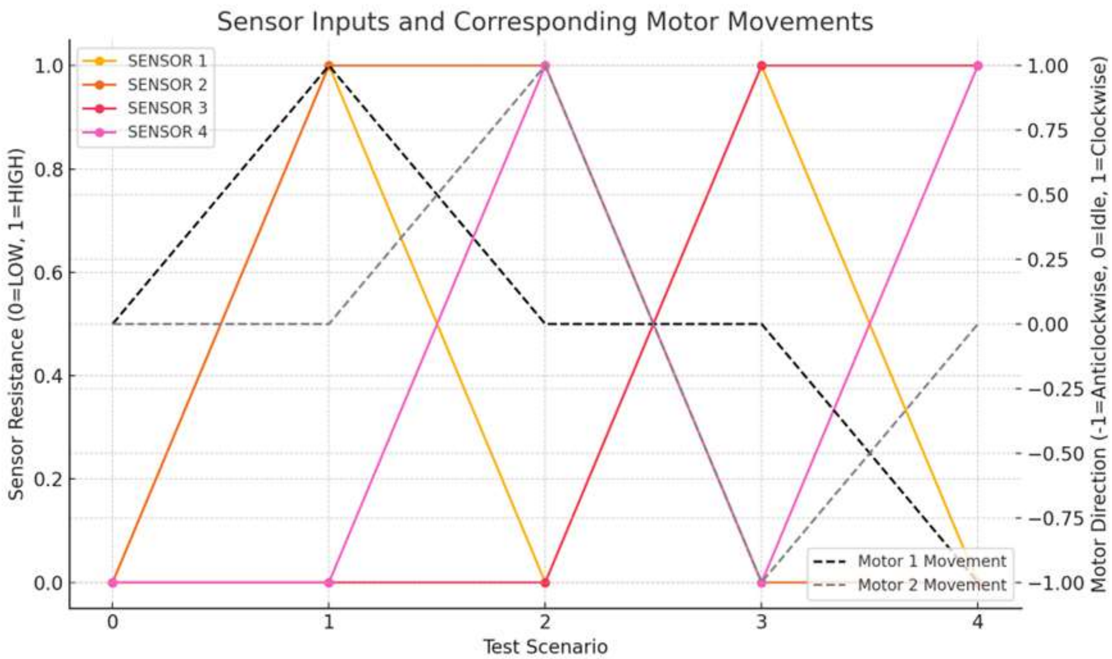

Fig. 4.1: Sensor Inputs and Corresponding Motor Rotations.

4.2 Discussion
From the table above, it would be seen that sensor 1 and sensor 2 are the top sensors in the first and second quadrant. Sensor 2 and sensor 4 are in the first and 4th quadrant; sensor 1 and 3 are in the second and third quadrant; sensor 3 and 4 are in the third and fourth quadrant. As the incident sun light radiate more energy at the top sensors, the motor will operate in such a way as to balance the intensity of the sun light on all the sensors at the same time. Hence the motor rotates clockwise by adjusting the solar panel to receive maximum energy. When the bottom sensors experience more intensity of light

than the others, the motor rotates in that direction as to balance all the sensors to same light intensity as the bottom sensors. The same occurs for the left top sensor and left bottom sensor as well as the right top sensor and right bottom sensor.

The objective is to position the solar panel for maximum energy from the sun. This approach ensures that the panel receives maximum energy at every point in time to charge batteries.

5.0 Conclusion, Summary and Recommendation

5.1 Conclusion

The design and construction of a solar tracking system integrated with Maximum Power Point Tracking (MPPT) has proven to be an effective solution for maximizing the efficiency of solar energy generation. By utilizing Light Dependent Resistors (LDRs) to detect sunlight intensity, an Arduino microcontroller for control logic, an L298N motor driver, and a DC wiper motor for mechanical movement, the system was able to accurately follow the sun's path throughout the day. The MPPT algorithm further enhanced system performance by ensuring the solar panel consistently operated at its optimal power point. Performance comparisons between the tracking system and a fixed-panel setup demonstrated a significant increase in energy output, confirming the effectiveness of the dual-axis tracking mechanism. The system not only improved solar energy harvesting but also proved to be economically feasible for practical applications. Overall, the project successfully achieved its objectives, offering a low-cost, efficient, and scalable solution for enhancing photovoltaic system performance in real-world conditions.

5.2 Summary

This project successfully designed and implemented a dual-axis solar tracking system integrated with Maximum Power Point Tracking (MPPT) to improve the efficiency of solar energy collection. Key components such as LDR sensors, an Arduino microcontroller, an L298N motor driver, and a wiper motor were used to create a system that automatically adjusts the solar panel's orientation based on the sun's position. The MPPT feature ensured the panel consistently operated at its highest power output. Comparative testing showed that the tracking system significantly outperformed a fixed solar panel, with increased energy generation and better efficiency. The project demonstrated that using affordable, readily available components can yield a practical and effective solution for maximizing solar energy in residential and commercial applications.

5.3 Recommendations

1. Use of Higher-Efficiency Motors: Although the wiper motor used performed adequately, replacing it with a more energy-efficient servo or stepper motor could reduce power consumption and improve tracking precision.
2. Integration of Weather Sensors: Incorporating sensors to detect rain, wind, or cloud cover can help protect the system and enable intelligent decision-making during adverse weather conditions.
3. Advanced MPPT Algorithms: Future versions of the system can adopt more advanced MPPT techniques such as Perturb and Observe (P&O) or Incremental Conductance to further enhance power extraction efficiency.
4. Data Logging and Remote Monitoring: Adding IoT features to enable remote performance monitoring and data logging could improve system management and allow for predictive maintenance.
5. Scalability for Larger Installations: The current system should be further developed and tested for scalability to suit larger solar farms or industrial-scale power generation.
6. Improved Structural Design: Enhancing the mechanical design for better durability and resistance to environmental wear will make the system more suitable for long-term outdoor use.
7. Battery and Storage Optimization: Optimizing the energy storage aspect (battery sizing and charge control) could help maintain system balance and ensure uninterrupted power supply.

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