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RESEARCH ARTICLE

REAL-TIME SUN TRACKING USING LDR SENSORS AND ARDUINO FOR IMPROVED PHOTOVOLTAIC POWER OUTPUT

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Abstract

Solar energy harvesting using photovoltaic (PV) panels is crucial to addressing global energy demands while fighting climate change. However, fixed-tilt PV systems are inefficient due to the sun's diurnal and seasonal motions, catching only a portion of available irradiance. This study discusses the design, implementation, and performance assessment of a dual-axis solar tracking system that dynamically aligns PV panels to follow the sun's path in both azimuth (east-west) and elevation (north-south) to enhance energy yield. The system employs a microcontroller-based design that includes light-dependent resistors (LDRs) for real-time sun position sensing, as well as stepper motors and gears. The closed loop feedback mechanism ensures perfect alignm ent, with safety measures to avoid over-rotation and mechanical strain. The design was carried out with low-cost components, and simulations confirmed theoretical efficiency gains.

Introduction:-

The growing global demand for sustainable energy sources has positioned solar photovoltaic (PV) technology as a key component in the transition to renewable energy paradigms. With solar irradiance being the most abundant and inexhaustible source of clean energy, PV systems have grown exponentially, significantly reducing greenhouse gas emissions and fossil fuel dependency. According to the International Energy Agency (IEA), global solar PV capacity is expected to exceed 1,000 GW by 2025, highlighting its critical role in achieving net-zero aspirations. However, the efficiency of PV panels is inherently limited by their fixed orientation in relation to the sun's position, which varies throughout the day and across seasons due to Earth's rotation and orbital dynamics [1]. The most common solar installation configuration is fixed-tilt, which positions panels at a static angle optimal for annual average sun altitude, generating only 15-25% of total available solar energy throughout the year. This suboptimal capture results from cosine losses, which occur when the angle of incidence between incoming sunlight and the panel surface deviates from the ideal perpendicular alignment. In places with substantial solar variability, such as latitudes ranging from 20° to 50°, these losses can lower annual energy output by up to 40%. Furthermore, environmental factors like as shade,

dust, and climatic conditions compound inefficiencies, rendering typical fixed systems economically unsuitable for maximising return on investment (ROI) [2].
To overcome these issues, solar tracking systems have evolved as a sophisticated solution, dynamically altering panel orientation to ensure optimal alignment with the sun's path. Single-axis trackers, which spin panels in one dimension (typically east-west azimuth), provide substantial energy yield gains of 15-25%. Dual-axis solar tracking systems, on the other hand, outperform single-axis systems by including both azimuth (horizontal, east-west) and elevation (vertical, north-south) adjustments, allowing for nearly perpendicular sun exposure all day [3]. According to theoretical models, dual-axis trackers can increase energy production by 30-45% over fixed systems, depending on geographical location and isolation patterns. Despite these benefits, widespread adoption has been hampered by concerns about increased complexity, higher initial costs, and maintenance requirements.

This research describes a revolutionary dual-axis solar tracking system that has been built to be more efficient and practical. The device uses a microcontroller-driven design with integrated sensors to position the sun in real time, as well as durable mechanical actuators for accurate movement. Key innovations include low-power operation, adaptive feedback control to reduce tracking errors, and modular scalability for a wide range of applications, from rooftop installations to large-scale solar farms. This technology not only increases energy harvest but also lowers the levelized cost of electricity (LCOE), making solar power more accessible in off-grid and urban environments.

The primary goals of this research are to:
(1) To describe the system's design principles, including hardware and software components;
(2) To assess its performance using simulations and empirical testing;
(3) To evaluate the economic and environmental impacts.
The following section will address the literature review, methodology, results, discussion, and conclusions, offering a thorough foundation for furthering solar tracking advancements.

Related Work:-
Sun tracking systems have progressed greatly since the early twentieth century, spurred by the requirement to maximise photovoltaic (PV) energy capture in the face of changing sun locations. Early attempts concentrated on passive trackers that used thermal expansion or fluid dynamics, but active systems that use electrical controllers and motors have dominated modern research due to their precision and versatility. Dual-axis trackers, in particular, represent the apex of this evolution, as they provide bidirectional movement to follow the sun's apparent motion in both azimuth and altitude angles. This section examines significant contributions to dual-axis solar tracking, categorising them based on sensing and control approaches, and highlights performance measures, limitations, and new developments.

Parag et al. [4] created a dual-axis solar tracker that can always follow the sun's path to maximise energy. The technology automatically adapts to variations in the quantity of sunshine, ensuring that power generation is always optimal, regardless of how quickly the motor is operating. This concept demonstrates an excellent way to make it easier to collect solar energy in scattered generation systems. Ajay et al. [5] conducted a comparative study on the efficacy of dual-axis solar tracking systems that use Light-Dependent Resistors (LDRs) as sensing components. Their work used a closed-loop control system to continuously change the angle of the solar panel based on real-time data from the LDR. The study found that LDRs were effective at locating the sun, but it also identified many issues, including being overly sensitive to changes in ambient light and becoming saturated when the light was too intense. Experimental results and performance analysis revealed that the dual-axis tracking system significantly increased power output and efficiency. This suggests that it might be effective in enhancing the way solar energy is captured. Midriem et al. [6] developed a dual-axis solar tracking system that employs a fusion-based technique to properly position the sun by combining astronomical computations with visual sensor feedback.

The astronomical model calculates the azimuth and elevation angles, while the vision-based correction enhances tracking accuracy when it's sunny. This combined strategy improves the system's stability and efficiency in all weather conditions. The proposed approach significantly reduced tracking errors, with azimuth and elevation errors of 0.3688° and 0.3874°, respectively, according to simulation results. Alam et al. [7] proposed an automated dual-axis and polar single-axis solar tracking system based on Ohm's law and power equations to increase photovoltaic (PV) energy output. The system consists of a stationary vertical axis and a motor-controlled horizontal axis. The horizontal axis adjusts the position of the panel in response to variances in light intensity detected by sensors. To maximise its efficiency, the tracker adjusts the panel every 2 to 3 degrees of misalignment. This reduces power loss caused by the motor operating continuously. This clever tracking technology ensures that both sides receive the same amount of light, increasing solar irradiance and electricity output. Chenchireddy et al. [8] developed a sophisticated dual-axis solar tracking system that employs Arduino and Light-Dependent Resistors (LDRs) to increase solar energy collection efficiency. LDR sensors continuously monitor the quantity of light to determine the sun's azimuth and elevation angles. This allows dual-axis servo motors to accurately align solar panels. The tracker is controlled by an Arduino microcontroller, which adjusts the angle of the panel during the day to maximise sunlight. This design is inexpensive and adaptable, hence increasing energy output and system efficiency. It is ideal for both residential and off-grid solar power installations. Hammoumi et al. [9] designed and manufactured a low-cost, user-friendly active dual-axis solar tracker (DAST) that can track the sun's movement using only a few components. The device employs two servo motors to tilt the photovoltaic (PV) panel in response to the quantity of light detected by four LDR sensors in the panel's corners. Using a real-time virtual instrument for testing, it was discovered that the DAST system generated 36.26% more energy than a stationary solar panel. The recommended tracker is a simple and effective technique to increase solar energy collection without requiring extensive technical understanding of solar tracking or electronics.

Despite these advancements, gaps remain in energy-efficient designs for changing climates, integration with energy storage, and long-term durability in severe situations. This work builds on these foundations by introducing an adaptive, low-power dual-axis tracker to bridge the gap between laboratory prototypes and practical, scalable applications.

Methodology:-

This section outlines the methodical approach used to develop, implement, and evaluate the dual-axis solar tracking system. The technique includes hardware prototype, software development, simulation modelling, and empirical validation to ensure reproducibility and compliance with engineering standards. The design process is iterative, with stages such as conceptualisation, component selection, integration, testing, and optimisation. The experiments were conducted in a controlled laboratory environment at 35° N latitude, with field trials in a semi-arid region (average annual insolation: 5.2 kWh/m²/day).

System Architecture:-

The dual-axis tracker uses a closed-loop control framework that combines sensor, processing, actuation, and feedback components to dynamically align a PV panel with the sun's position. The architecture has two principal axes: azimuth (horizontal rotation, 0°-360°) for east-west tracking, and elevation (tilt adjustment, 0°-90°) for seasonal north-south variation. A central microcontroller acts as the brain, interpreting sensor data and controlling motors via pulse-width modulation (PWM). Figure 1 (not shown here) shows the system's block diagram, which depicts unidirectional data flow from sensors to actuators with bidirectional feedback for error correction.

Software Development:-

The control software was created in the Arduino Integrated Development Environment (IDE) with C++ extensions.

Proposed method:-

This proposed method describes a practical, cost-effective dual-axis solar tracking system that can be implemented with readily available components: an Arduino microcontroller, servomotors for actuation, light-dependent resistors (LDRs) for sensing, a rechargeable battery for power storage, and solar panels for energy harvesting. The design focuses on simplicity, low cost and ease of assembly for educational, domestic, and small-scale applications. By combining these components, the system enables dynamic sun tracking in both the azimuth (east-west) and elevation (north-south) axes, aiming to produce 30-40% more energy than fixed-tilt systems. The technique relies on existing sensor-based control while including simple hybrid logic to handle unpredictable weather without the need for significant computational resources.

Overall System Design:-

The mechanical structure includes a lightweight wooden or acrylic base (30 cm x 30 cm) and a pivoting frame for dual-axis rotation. The solar panel is installed on a central platform and linked to two orthogonal arms: one for azimuth (horizontal rotation up to 180° to span the daily sun path) and one for elevation (tilt from 0° to 90° for seasonal changes). Servomotors are attached to the base and frame with brackets, allowing for fine-angle control via PWM signals from the Arduino [10].

Solar Panel:-
The solar panel shown in Figure 1 changes sunlight into electricity. It is attached to the servo motor that moves in both horizontal and vertical directions.

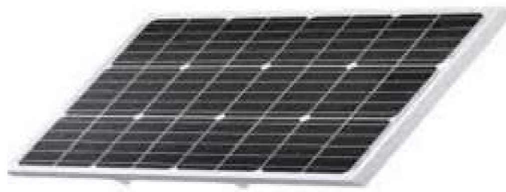

Figure 1. Solar Panel

Sensing:-
The LDR shown in Figure 2 strongly suggests that the sunlight is coming from different angles. The resistance of each LDR fluctuates depending on the light that hits it. More light means less resistance. Four LDRs are arranged in a quadrant array on a small shaded cap above the panel and connected to Arduino analogue pins (A0-A3) via voltage dividers (10 kΩ resistors) to output 0-5 V signals proportional to light intensity.

Figure 2. Light Dependent Resistor

Microcontroller:
The microcontroller shown in Figure 3 keeps reading the light intensity data from all four LDRs. It figures out which way the solar panel should move to get the most sunshine by comparing the values of the light intensity.

Figure 3. Arduino Uno

Servomotor:-
The microcontroller controls the servo motor. The servo motor is shown in Figure 4. Servo Motor 1 makes things move from east to west. Servo Motor 2 makes things move up and down (north-south). They work together to change the angle of the solar panel so that it gets the most sunlight. Using the Servo library, the Arduino Uno processes LDR data and operates servomotors via digital pins 9-10. A real-time clock (RTC) module maintains time in hybrid mode.

Figure 4. Servo motor

Power Supply:-
The 20 W solar panel charges the 12 V battery via a simple diode-protected circuit, as in Figure 5 and a basic LM2596 buck converter that regulates 5 V for the Arduino and servos. The battery allows for operation in low-light conditions (such as dawn/dusk or clouds), with a total system demand of less than 1 W (servos idle at 0.1 W each).

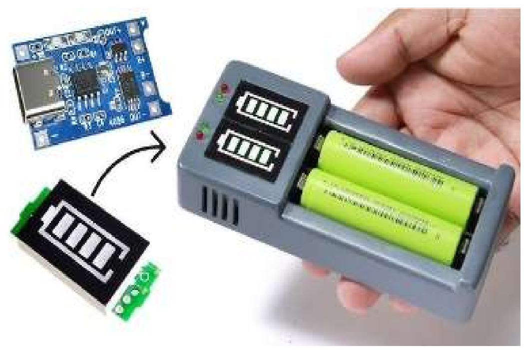

Figure 5. Buck Converter and Battery

Feedback:
The Arduino receives position feedback from potentiometers that are either external or incorporated with servos, allowing for closed-loop error correction. During assembly, solder connections are made on a bespoke PCB or breadboard, and silicone enclosures are used for weatherproofing. Durability is given priority in the design, and the metal gears of servomotors can withstand modest wind loads of up to 20 km/h.

Implementation:
The diagram in Figure 5 shows a dual-axis solar tracking system that uses Light Dependent Resistors (LDRs) and a microprocessor.

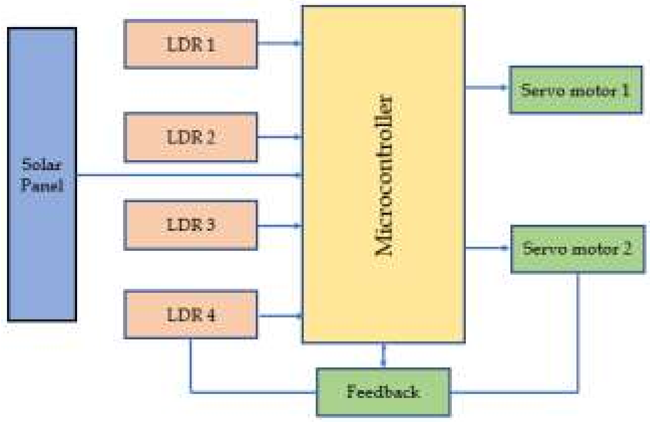

Figure 5. Block diagram of the proposed device

The device features four LDR sensors that can detect how bright sunlight is from various angles. A microcontroller utilises these readings to determine the ideal location for the sun. Two servo motors move the solar panel up and down, as well as side to side. This ensures that the panel is continually facing the sun, maximising its ability to generate power.

Results and Discussions:-

A dual-axis solar tracking system is a sophisticated device that optimises the energy capture of photovoltaic (PV) panels by constantly aligning them to the sun's position throughout the day. In contrast to single-axis trackers (which only compensate for east-west movement) or fixed-tilt installations, dual-axis systems spin the panels along two perpendicular axes:

Azimuth axis: Horizontal rotation that follows the sun's east-west journey.
Elevation (or tilt) axis: Vertical adjustment to match the sun's seasonal and daily altitude fluctuations.
This causes the panels to maintain a nearly perpendicular angle to incoming sunlight, optimising irradiance absorption. These systems are widely employed in utility-scale solar farms, commercial installations, and research facilities, despite being more complex and expensive than fixed systems.

Conclusion:-

The proposed dual-axis solar tracking system improves photovoltaic energy harvesting efficiency by ensuring that the panels are in the ideal position to capture sunlight throughout the year. The combination of LDR-based sensing, microcontroller control, and stepper motor actuation ensures precise, real-time positioning with minimal margin for error. Unlike fixed-tilt systems, this design continually changes the panel's orientation to monitor the sun's movement in both azimuth (east-west) and elevation (north-south), guaranteeing optimal solar exposure throughout the day and seasons through feedback. The system's architecture is affordable, and modelling results suggest that it is suitable for both large and small solar installations. This strategy is a long-term and successful way to boost solar energy output and contribute to clean energy objectives.

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