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Smart Solar-Tracking System for Maximizing Energy Output

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Abstract

This paper presents the design and development of a dual-axis solar-tracking system using a stepper motor and light-dependent sensors to maximize solar energy capture. The proposed system continuously aligns the photovoltaic panel perpendicular to the Sun's rays, thereby improving overall power-generation efficiency. A complete prototype was developed and experimentally tested. To assess system performance, experimental testing was carried out in a variety of lighting and environmental settings. When compared to fixed solar panels, the results show a significant increase in energy generation, demonstrating the tracking mechanism's efficacy. According to the results, dual-axis tracking systems provide a dependable and effective way to increase solar power generation, which makes them appropriate for uses that call for increased energy yield and the best possible use of renewable energy sources. To verify the suggested method, a fully working prototype was created. The design process addresses sensor calibration, control logic implementation, mechanical framework building, and hardware component selection. To evaluate the tracking mechanism's efficacy, experimental testing was conducted in a variety of weather and illumination scenarios. When compared to fixed solar panels of comparable ratings, the performance study reveals a discernible improvement in electrical energy generation. The outcomes demonstrate that the dual-axis tracking system improves the efficiency of solar energy capture and makes greater use of the daylight that is available throughout the day. The design methodology, hardware implementation, and performance analysis are discussed in detail, demonstrating significant improvement over fixed solar panels.

Keywords: Renewable energy, power optimization, dual-axis solar tracker, light-dependent resistors (LDRs), solar panel efficiency enhancement

INTRODUCTION

The extraction of usable electrical power from sunlight became possible with the discovery of the photoelectric effect and the subsequent development of modern solar cells, which are semiconductor devices capable of converting incident light into direct current (DC) [1–4]. When multiple solar cells are electrically interconnected to form a solar array, a practical DC voltage is produced that can be supplied to various loads. With continuous efficiency improvements, solar panels are now widely deployed, particularly in remote regions where installing conventional transmission lines is not economically feasible [5–7].

The growing concerns regarding the limitations of fossil fuels have accelerated the adoption of renewable energy sources. Solar, wind, hydroelectric, and geothermal power have been

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utilized for nearly a century with varying degrees of success. Among these, hydro and wind energy remain the most extensively used, whereas solar power has seen moderate global adoption owing to its historically high production costs and relatively low conversion efficiency [8–11]. However, intensive research and advancements in photovoltaic technology have significantly reduced the cost of solar energy, bringing it closer to the cost per kilowatt-hour of conventional generation. Emerging technologies, including titanium oxide–based cells, continue to push efficiency boundaries. With laboratory efficiencies reaching up to 32% and commercial modules typically achieving 15–20%, it is increasingly important to maximize the energy captured from solar power systems [12–15].

This involves minimizing the losses associated with the inverter, energy storage system, and light-collection process. The light-collection efficiency is strongly influenced by the angle of incidence of sunlight on the solar cell surface; the closer this angle is to perpendicular, the higher the resulting power output [16–20].

When a solar panel is placed on level ground, the angle of incidence of sunlight varies significantly during the day. During the early morning and late evening, the Sun's rays strike the panel at a very shallow angle, close to 90°, resulting in almost no effective light collection and minimal power output. As the Sun rises toward midday, the angle of incidence decreases gradually, approaching 0°. This leads to a steady increase in power generation, reaching a maximum when sunlight is perpendicular to the panel surface.

After midday, the angle of incidence began to increase again as the Sun moved toward the horizon, causing a corresponding reduction in the power output.

This behavior highlights the importance of maintaining an angle of incidence as close to 0° as possible to ensure maximum energy harvesting efficiency. This condition can be achieved by continuously adjusting the orientation of the solar panel to face the Sun. The method of detecting and following the Sun's position in real time is known as solar tracking. Real-time tracking was determined to be the most effective approach to ensure reliable operation without relying on external data or preprogrammed positions.

THE SENSING ELEMENT AND SIGNAL PROCESSING

Techniques have been developed to track the position of the Sun throughout the day. One of the simplest approaches employs a light-dependent resistor (LDR) to sense variations in light intensity. More advanced methods, such as the design reported, in Home Power, utilize a pair of phototransistors with a small shading plate positioned between them. This arrangement creates a differential light-sensing effect, enabling the system to determine the direction of the Sun, as illustrated in Figure 1 [21].

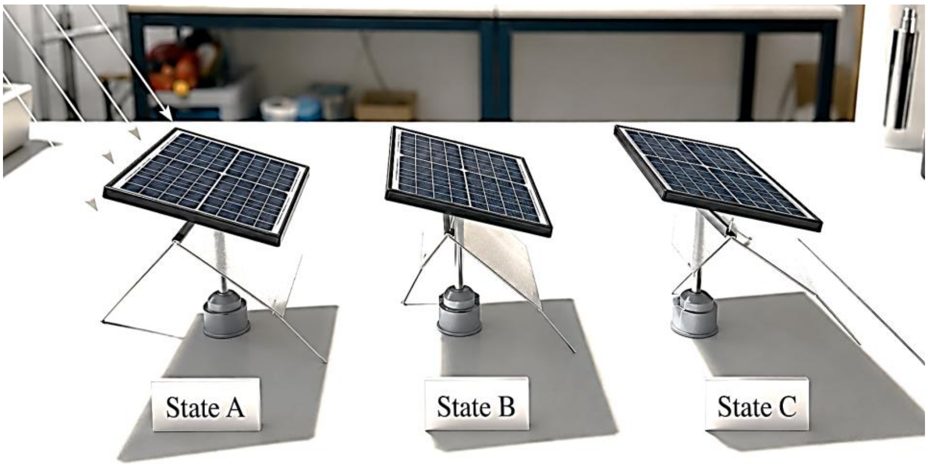

Figure 1. Alternative solar-tracking method.

In Sunrise, the tracking system begins in State A, which is the final position from the previous day. In this state, the left phototransistor is illuminated and activated, generating a control signal that rotates the motor until the shading plate aligns with the sensors, and the system returns to State B. As the Sun continues to move across the sky, the tracker eventually reaches State C, where the right phototransistor becomes active. The motor then rotates again until the sensor output returns to State B. This sequence is repeated throughout the day or until the ambient light falls below the minimum detectable level [22].

However, a key limitation of this approach is the narrow sensitivity range of the phototransistors when configured under fixed-bias conditions. To overcome this constraint, solar cells were selected as sensing elements. Solar cells exhibit excellent sensitivity to varying light levels and provide a nearly linear voltage response, making them well suited for accurately determining the Sun's declination angle [23]. Based on this advantage, a simple triangular sensor arrangement was developed, consisting of two solar cells positioned in opposite directions, as shown in Figure 2.

In the neutral or rest position, both solar cells received equal amounts of sunlight. Although the angle of incidence is not exactly 0°, it is symmetrically distributed across both cells, resulting in equal output voltages, as shown in Figure 3.

As shown in Figure 4, when the Sun changes its position in the sky while the solar tracker remains stationary, the angle at which sunlight strikes the reference panel changes accordingly. This variation causes one photodiode or solar cell to receive more light than the other photodiode or solar cell. As a result, a measurable voltage difference was produced, with the cell receiving higher illumination generating greater potential. This voltage imbalance creates a detectable signal at each cell, which can be interpreted and processed by an appropriate control circuit.

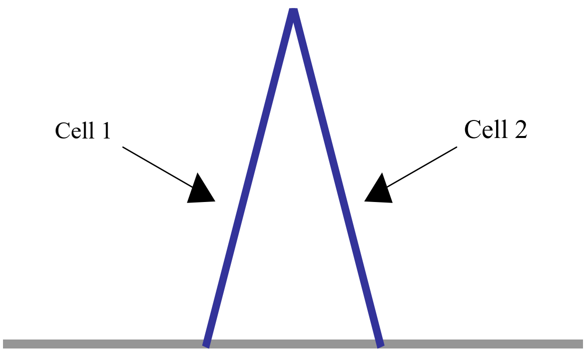

Figure 2. Setup of solar reference cells.

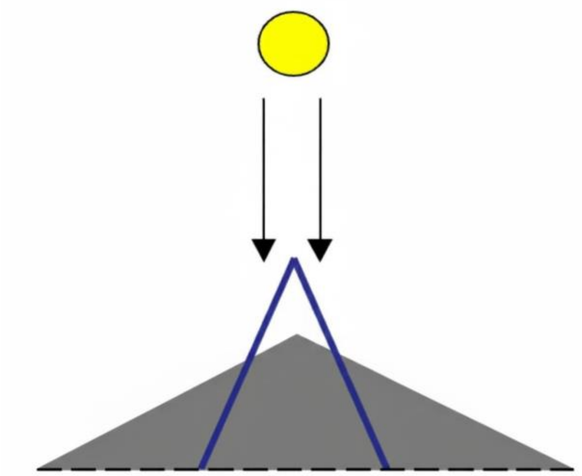

Figure 3. Solar reference cells at rest position.

A PROTOTYPE SOLAR TRACKER

The final stage involved integrating the control circuitry with the motor and securely mounting the assembly onto the bracket. The completed prototype is illustrated in Figure 5. A Solarex 9 W polycrystalline silicon solar module borrowed from the technical department was installed on the flanges of the tracker.

Two test procedures were conducted for performance evaluation. In the first test, the solar panel was detached from the tracking system and placed in a fixed and flat orientation. The panel output was connected to a load designed to dissipate approximately 9 W, corresponding to its rated power. Because 9 W at 12 V yields a current of 0.75 A, the required load resistance was calculated using Ohm's law ($R = V/I$) to be approximately 16 Ω. The closest available component was a 15 Ω, 50 W resistor that was used as the load.

The tracking system required an external power supply, which was provided by a 12 V battery connected to the solar panel in a charging configuration. The voltage across the load and the current through it were measured using two separate multimeters. Measurements were recorded at half-hour intervals on clear, cloud-free days and entered into an Excel spreadsheet for analysis. The data collected were used to generate the graph shown in Figure 6.

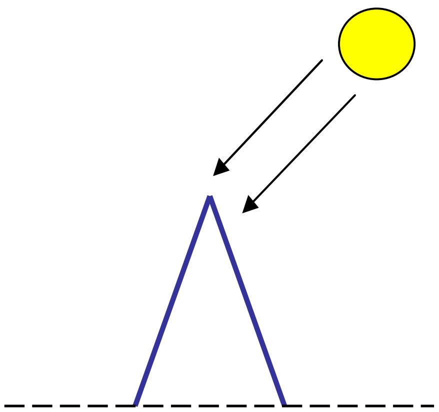

Figure 4. Solar reference cells at a significant angle to the Sun.

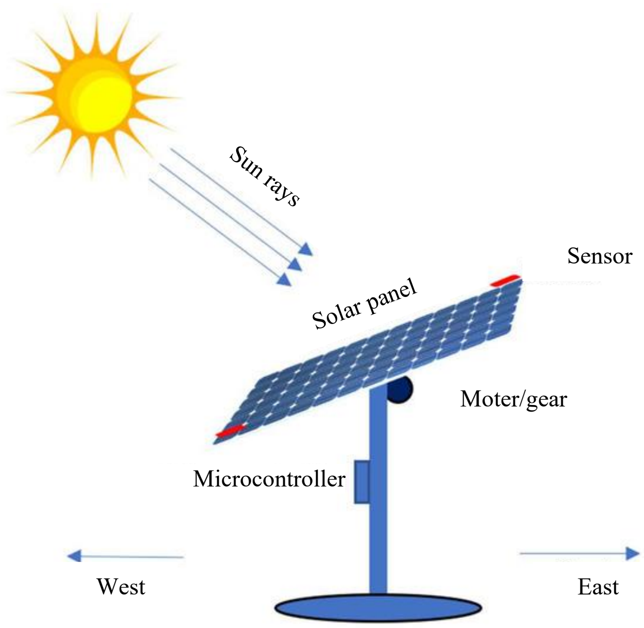

Figure 5. A prototype solar tracker.

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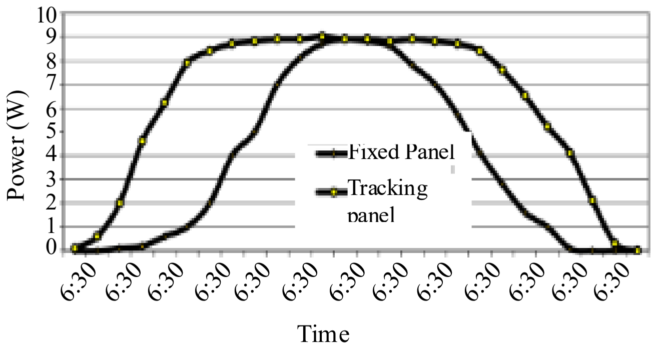

Figure 6. Experimental results of power increase for tracked panels.

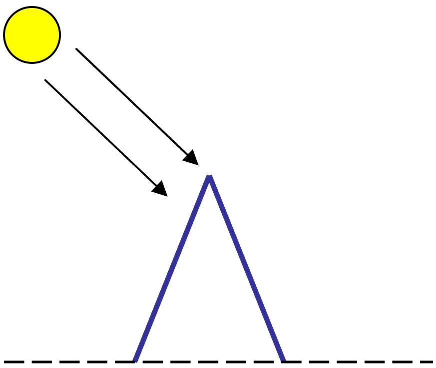

Figure 7. Schematic illustration of a mountain peak under sunlight.

Using Excel, the percentage and average power increases were calculated from recorded data. For the fixed solar panel, the average output over 12 hours was approximately 39% of its rated 9 W capacity, resulting in an average power of 3.51 W. In comparison, the tracking system delivered an average of 71% of the panel's rated output, which is equivalent to 6.3 W over the same duration. During the early morning and late afternoon, the tracked panel produced up to 400% more power than the fixed panel (Figure 7). Overall, maintaining the panel as close to perpendicular to the Sun as possible yielded an average power improvement of 30%.

To verify that the tracking system did not consume excessive power, the current drawn by the device was measured. When the tracker was stationary, an ammeter was connected in series with the battery, and the current was recorded as 4 mA at 12 V. This corresponds to a standby power consumption of approximately 48 mW, indicating minimal self-power consumption.

DISCUSSION

A solar-tracking system was proposed, designed, and constructed successfully. The final prototype demonstrated a substantial improvement in power collection efficiency, increasing the average output from 39% for a fixed solar panel to over 70% when the same panel was mounted on the tracking device. In practical terms, this enhanced energy capture can significantly reduce the overall system cost because a solar array equipped with a tracking mechanism can deliver considerably more power. By extracting greater energy from an existing panel, the effective cost per watt is lowered, making solar power notably more economical than traditional fixed-panel installations.

Historically, the high upfront cost of commercial solar trackers has limited their widespread use, despite their ability to improve the overall energy yield. Many commercially available units exceed US$2000, especially those designed to support the weight of large solar panels while providing reliable Sun-tracking capability. In contrast, the device developed in this project is capable of supporting loads of up to 8 kg, which is approximately the weight of a typical 75 W solar module, owing to its robust yet simple design and high torque output of the motor.

Moreover, the prototype was constructed at an exceptionally low cost using mostly recycled or salvaged components. The total material expenditure, excluding the 9 W solar panel, was approximately A$30. The geared mounting system was repurposed from an old security camera, the stepper motor was obtained from a discarded printer, and the remaining mechanical and electronic components, including the reference solar cells, were sourced from various scrap materials. This demonstrates that an efficient and functional solar-tracking system can be assembled economically without relying on expensive commercial hardware.

If the components used in this prototype were purchased rather than sourced from scrap materials, the total cost is estimated to remain below A$100. Although the constructed device is a single-axis tracker and already provides a substantial improvement in power output compared to a fixed solar panel, a dual-axis tracking system could deliver even higher efficiency. This presents an opportunity for future enhancements and further research.

Solar tracking remains one of the most effective and accessible methods for improving the overall efficiency of domestic and commercial solar power systems. With the simplicity of the proposed design, individuals can feasibly construct the tracker themselves, enabling a low-cost, high-performance solution for maximizing solar energy collection.

CONCLUSION

The solar tracker was designed based on a novel approach that utilized small solar cells as self-adjusting light sensors. These cells generate a voltage proportional to their orientation relative to the Sun, thereby providing a continuous indication of alignment. Using this principle, the tracker effectively maintained the solar array at an angle that was closely perpendicular to the incoming sunlight. As a result, the system achieved a power gain of more than 30% compared with a fixed horizontally mounted array.

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