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Analysis Of Solar Tracking Device Design And Development For Improved Solar Panel Performance

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Abstract

This paper focuses on designing and building a passive solar tracking system to improve the performance and efficiency of solar power systems. The proposed system utilizes passive techniques that eliminate the need for active control mechanisms or external power sources, thereby reducing complexity and energy consumption. The paper encompasses the conceptualization, design, prototyping, and testing of the passive tracking system to optimize the angle at which sunlight strikes the solar panels.

The design process begins with an in-depth exploration of solar tracking principles, including the Sun's movement, geographical factors, and how the incident angle affects energy capture. Various passive tracking methods, such as bimetallic strips, compressed gas systems, and shape memory alloys, are examined to identify the most appropriate approach for the paper.

Based on the analysis, a new passive tracking mechanism is developed, considering aspects like simplicity, reliability, cost-effectiveness, and adaptability to various solar panel configurations. The design features mechanical components like linkages, gears, and pivots that allow the system to automatically follow the Sun's path throughout the day.

The expected outcome of this paper is to demonstrate the practicality and advantages of a passive solar tracking system in boosting energy production and maximizing the use of solar resources. The results could contribute to the development of more efficient and cost-effective solar power systems, especially in situations where active tracking systems may not be feasible or economically viable.

Keywords: Passive solar tracking system, solar power systems, incident angle optimization, mechanical design, manufacturing, energy efficiency.

Introduction

Solar energy is gaining popularity due to its renewable nature, widespread availability, and decreasing costs, making it a sustainable, accessible, and cost-effective power source with minimal environmental impact. As a reliable and sustainable form of renewable energy, solar power is increasingly favored for its cost-effectiveness and dependability. In agriculture, solar energy is becoming a valuable resource, providing farmers with a consistent and eco-friendly energy source for irrigation, crop drying, and other essential activities. However, the efficiency of solar panels in agricultural applications can be enhanced by integrating a single-axis sun-tracking mechanism.

This paper aims to design and develop a passive solar tracking system with single-axis tracking. Unlike traditional systems, this design does not rely on electrical power for panel rotation. Instead, mechanical power is used, with energy stored in a spiral spring. Through a gear arrangement, the speed is reduced to match the Sun's movement throughout the day.

The primary objective of this paper is to design a tracking system for both domestic and industrial solar panels, aiming to improve their efficiency and performance.

Solar energy is a renewable and sustainable power source that is rapidly gaining popularity worldwide due to its numerous benefits. The sun generates energy through nuclear fusion, emitting light and heat, which is then captured and converted into electricity by solar panels. Solar energy offers several advantages, including a reduced environmental impact, decreased reliance on fossil fuels, and greater energy independence.

One of the key benefits of solar energy is that it is a clean and renewable resource. Unlike fossil fuels, solar energy does not produce harmful emissions that can harm the environment and contribute to climate change. Additionally, solar panels require no fuel to generate electricity, meaning they incur zero fuel costs and produce no waste or pollution. Another significant advantage is that solar energy is a decentralized power source, allowing solar panels to be installed on rooftops, in remote locations, or in areas without access to the traditional power grid. This is especially important in developing countries, where reliable access to electricity is often limited or unavailable.

Solar radiation, or solar energy, refers to the electromagnetic radiation emitted by the Sun. It is the primary energy source for Earth, driving various natural processes and supporting human activities. This overview will cover the characteristics, components, measurement, and importance of solar radiation.

Solar radiation spans a wide range of electromagnetic waves, from high-energy gamma rays and X-rays to lower-energy ultraviolet (UV) rays, visible light, and infrared (IR) radiation. However, only a small portion of this spectrum is significant for solar power generation and biological processes on Earth.

The intensity of solar radiation is influenced by factors such as the time of day, season, geographic location, and atmospheric conditions. The angle at which sunlight hits the Earth's surface determines the amount of energy received. Solar radiation is most intense when the Sun is directly overhead, typically at noon. During sunrise or sunset, sunlight must travel through a thicker portion of the atmosphere, resulting in lower intensity and a longer path to the Earth's surface.

The Earth's atmosphere serves as a filter for solar radiation, allowing some wavelengths to pass through while absorbing or scattering others. For example, UV rays are mostly absorbed by the ozone layer in the stratosphere, which protects living organisms from harmful excess UV radiation. The visible light portion of solar radiation is the range that the human eye can perceive, consisting of various colors, each with a specific wavelength.

A solar tracking system is a device or mechanism designed to adjust the position of solar panels or mirrors in order to align them with the Sun, maximizing the absorption of solar radiation. The main objective of a solar tracking system is to optimize the angle at which sunlight hits the panels, ensuring they receive the highest possible solar irradiance throughout the day. This enhanced efficiency can significantly boost the energy output of solar power systems. There are two primary types of solar tracking systems: single-axis and dual-axis.

A single-axis tracking system adjusts the position of solar panels along a single axis, usually either horizontal (azimuth) or vertical (elevation). Horizontal single-axis systems rotate the panels from east to west, following the Sun's movement across the sky. This allows the panels to remain directly facing the Sun throughout the day. Vertical single-axis tracking systems tilt the panels to optimize the angle as the Sun's elevation changes. Single-axis systems are generally simpler and more cost-effective compared to dual-axis systems. The basic operation of a PV cell is illustrated in Fig. 1.

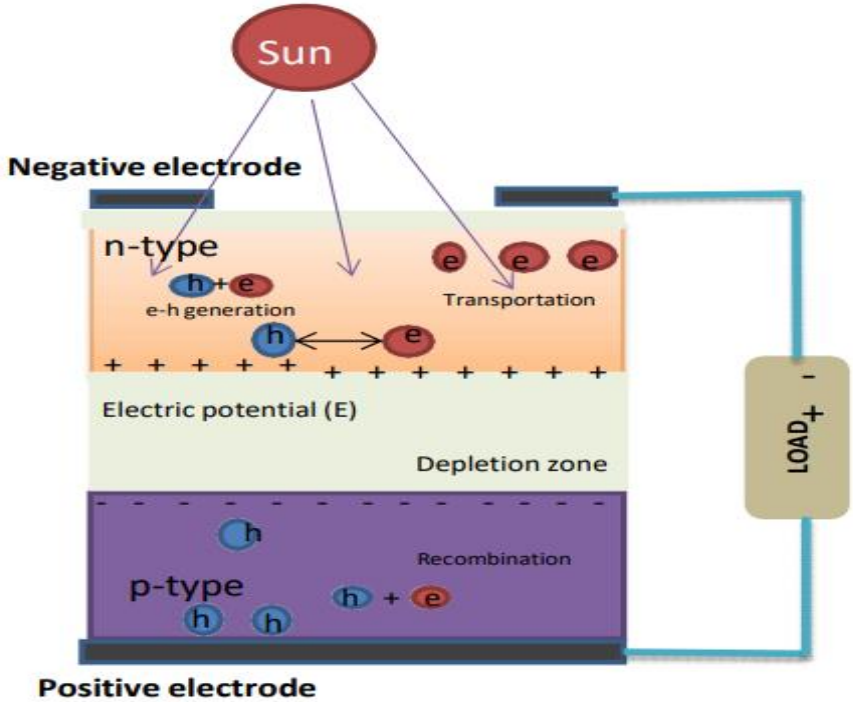

Figure 1: Solar Tracking Unit System

Literature Review

Renewable energy resources include solar, wind, hydro, fuel cells (FC), and others. Among these, solar energy stands out as a pollution-free, reliable, and promising green source to meet the growing energy demand. With the increasing need for energy, the depletion of conventional fuels, and the growing concern over environmental pollution, researchers have focused on developing new solutions to harness renewable energy.

The photovoltaic (PV) system converts sunlight into electrical power through the photovoltaic effect. When light strikes a PV cell, energy from photons is transferred to charge carriers. This causes the charge carriers to split into positively charged holes and negatively charged electrons due to the electric field at the junction. As a result, a current flows if a closed circuit path is provided by connecting a load. The global consumption of solar energy has risen exponentially, with both the total capacity and energy generated significantly increasing. The overall growth in solar energy capacity and usage has reached 29.6%.

Active and passive solar tracking are the two main techniques used to efficiently track the Sun. Active trackers account for 75% of applications, while passive solar trackers make up 7.5% of usage. Generally, trackers use light-detecting sensors, such as Light Dependent Resistors (LDRs), placed at the four corners of a photovoltaic (PV) cell. The microcontroller computes the average signals from the LDRs, then directs servomotors to adjust the PV panels toward the direction of maximum sunlight. Studies have shown that this tracking system can increase the generated output power by 54.71% compared to fixed solar panels.

Another study examined the performance of a dual-axis solar tracker with five PV cells at high altitudes (over 3800 meters above sea level). The system, powered by two linear actuators, automatically follows the Sun's trajectory throughout the day. Each PV cell independently measures solar irradiance, which is then processed by a Programmable Logic Controller (PLC). The PLC compares the current irradiance with the reference maximum value to optimize the motion of the tracker's axes and identify the point of maximum power. The study revealed that using tracking systems improves energy conversion efficiency by 24% to 30%. The dual-axis tracker, for example, produced 37.63% more energy monthly than the fixed system, generating 10.66 $kWh/m^2/day$, compared to the fixed system's 7.75 $kWh/m^2/day$. On cloudy days, however, both systems' performance dropped to 14.38%, but this may vary by region depending on sun availability.

When comparing fixed and tracking systems, a fixed PV module showed a 0.4% higher efficiency than a single-axis tracker. During the dry season, the sun tracker performed 0.5% better than the fixed system. The maximum efficiency of fixed PV installations was 12.4%, while the sun tracker achieved 13%. This demonstrates that solar trackers allow for greater solar radiation capture by maintaining the module's surface perpendicular to the Sun for longer periods, thus generating more electricity.

Further studies have shown that active single-axis and dual-axis solar tracking systems can increase electricity production by 15% to 45% compared to fixed systems of equal power. Dual-axis systems based on Light Dependent Resistors (LDRs) have achieved up to 19.97% higher efficiency, while low-cost systems with multiple LDRs have shown improvements of up to 40%. Systems using closed-loop control systems have reached a 54.39% increase in performance. Dual-axis solar trackers currently provide the greatest photovoltaic efficiency since they track the Sun's path across both horizontal and vertical axes.

To control solar tracking systems, several strategies are used, including open-loop, closed-loop, or combined systems. Classic methods such as ON-OFF, PI, and PID controls, along with control algorithms through Programmable Logic Controllers (PLCs), can manage these systems. Photo sensors or photodiodes are often used for solar tracking, though their performance is reliant on clear skies and favorable weather conditions. Some trackers use cost-effective LDRs or PV panels as alternatives. Additionally, the performance of solar trackers can be improved with Maximum Power Point Tracking (MPPT) strategies.

Several factors affect the performance of trackers, including weather conditions, altitude, precipitation, and cloud cover. Principal component analysis (PCA) is often used to analyze the impact of these factors on performance. This method categorizes variables effectively and helps in monitoring and detecting faults. The study also emphasizes that the performance of both types of trackers depends on factors like the actuators, mechanical components, materials, and the terrain where the system operates.

Another type of tracking system is passive, which uses mechanisms such as phase change materials that alter the physical properties of fluids when solar energy is absorbed, or it can rely on gravitational potential, spring mounting, or the integration of wind energy. One early attempt at a single-axis passive solar tracker utilized shape memory alloy (SMA) actuators, which proved to be more efficient than bimetallic actuators [16]. On the other hand, bimetallic laminates made of Ni36/Mn75Ni15Cu10 strips can be used as the main actuator for tracking. These strips change shape when they bend and deform due to temperature changes, influenced by the shadow area and the orientation of the solar cell to the light. The results of this method show good feasibility and stability in terms of the deformation process of bistable laminates. The study identifies the deformation capability, or "actuation effect," which is directly linked to tracking efficiency and is influenced by factors like snap-through temperatures, the arrangement of bimetallic strips, and the thickness of the strips, which were tested both numerically and experimentally with good overall results [17].

Clifford et al. designed a bimetallic strip tracker using two strips made of aluminum and steel, mounted symmetrically on either side of a central horizontal axis on a wooden frame. The strip facing the Sun absorbs thermal radiation, causing it to heat up. Due to aluminum's higher coefficient of thermal expansion, it bends more than the steel, resulting in a maximum deflection at the midpoint of the strip. This bending creates an unbalanced moment, causing movement toward the Sun and rotating the solar panel [18]. Another attempt by Suhail Zaki Farooqui et al. [19] developed a gravity-based solar tracker for a solar cooker, involving the actuation of a stretched spring and a mirror (as shown in Fig. 8).

In this system, water stored in a container is attached to a spring via a chord. As water is discharged at a constant rate from the container, the spring slowly returns to its un-stretched position, pulling the solar cooker with it. Additionally, the height of the booster mirror attached to the solar cooker is adjusted to track the changing solar elevation. By matching the rate of water discharge with the rate of change in solar azimuth, solar tracking can be achieved. The system was optimized to allow for 6 hours of cooking per day without manual tracking, resulting in an optimum booster mirror angle of 25 degrees.

Review Conclusion

Solar tracking systems offer significantly higher efficiency and performance compared to fixed or stationary solar photovoltaic systems. The primary advantage of solar tracking systems is the increased electricity generation, which depends on the geographical location of the tracker and other variables. However, solar tracking systems come with several limitations. They tend to be more expensive than fixed systems due to the complexity of the technology involved and the use of costly components for their operations.

Active trackers, which use optical sensors and microcontroller-based active drives, provide the benefit of precise tracking and are commonly used, often outperforming auxiliary bifacial and time-based active drives.

However, a common disadvantage is their lower efficiency on cloudy days, as the sensors require sunlight to operate effectively.

In contrast, passive drives rely on the changing physical properties of fluids, avoiding the need for complex control circuits, motors, gears, and sensors. This makes passive systems more cost-effective and viable compared to active systems. The energy output of both types of systems is influenced by factors such as the type of photovoltaic material, the geographic location of solar irradiance, ambient temperature and weather conditions, the angle of sun incidence, and the panel's orientation.

Conduct a thorough literature review on solar tracking systems, with an emphasis on both active and passive tracking methods. Examine the underlying principles, benefits, and drawbacks of various tracking approaches. Highlight key design factors, including optimization of the incident angle, mechanical components, and overall system efficiency.

Problem Definition

The main challenge is eliminating the power consumption required for solar tracking systems. The solution is to design a fully mechanical solar tracker. This paper aims to address the limited availability of sustainable and cost-effective power generation solutions for various environments, particularly in both residential and industrial settings. It also tackles the issue of suboptimal energy production and efficiency in conventional fixed-tilt solar power systems, which are unable to track the Sun's movement. Fixed-tilt systems have a static angle, resulting in reduced exposure to direct sunlight and less-than-ideal incident angles throughout the day. As a result, energy output is lower, and the full potential of solar radiation is not fully utilized.

Methodology

The design process for the proposed solar power system consists of several key steps:

1. **Defining the requirements:** This step involves identifying the system's power needs and determining its specific application, such as water pumping or irrigation in agricultural or domestic settings.
2. **Selecting components:** Based on the power requirements, appropriate solar panels, tracking mechanisms, and portable power units will be chosen.
3. **Designing the sliding mechanism:** A sliding mechanism will be created to enable the solar panel's movement, ensuring it is positioned optimally for maximum energy generation.
4. **Designing the tracking mechanism:** The tracking system will be developed to automatically adjust the solar panel's tilt angle according to the sun's position, maximizing energy output.
5. **Designing the portable power unit:** The portable power unit will be designed to offer flexibility in meeting power needs while ensuring ease of transportation.

6. **Integrating the components:** All selected components will be integrated into a unified solar power system that is efficient, portable, and adaptable to various environments.
7. **Testing and refinement:** The system will undergo testing and refinement to enhance its efficiency and performance, ensuring it fulfills the power requirements of the intended application.

Results

The paper involves the design and manufacturing of a passive solar tracking system. For the competition, we need to calculate the design specifications and materials. On average, the sun provides maximum intensity of solar radiation for about 8 hours per day. To track the maximum solar radiation, the solar plate needs to rotate through 120 degrees per day, matching the angular speed of the sun's radiation.

The solar plate has a mass of 3 kg and dimensions of 340 mm in length, 240 mm in width, and 20 mm in thickness. It must revolve through 120 degrees over 8 hours each day. The following calculations are needed:

Given Data:

- Mass of the rectangular flat solar plate (m): 3 kg
- Length of the plate (l): 0.34 m
- Width of the plate (w): 0.24 m
- Thickness of the plate (t): 0.02 m
- Angular displacement (θ): 120 degrees
- Time (t): 8 hours

Calculations:

1. Convert the angular displacement from degrees to radians:

$$\theta_{radians} = 120 \times \left(\frac{\pi}{180}\right)$$

$$\theta_{radians} \approx 2.094 \text{ radians}$$

2. Calculate the angular velocity (ω):

$$\omega = \frac{\theta_{radians}}{t}$$

$$\omega \approx \frac{2.094 \text{ radians}}{(8 \text{ hours} \times 3600 \text{ seconds/hour})}$$

$$\omega \approx 7.3 \times 10^{-5} \text{ radians/second}$$

3. Calculate the moment of inertia (I) for the rectangular plate:

$$I = \frac{1}{12} \times m \times (l^2 + w^2)$$

$$I = \frac{1}{12} \times 3 \text{ kg} \times \left((0.34 \text{ m})^2 + (0.24 \text{ m})^2\right)$$

$$I \approx 0.118 \text{ kg} \times \text{m}^2$$

4. Calculate the angular acceleration (α):

$$\alpha = \frac{\omega}{t}$$

$$\alpha = \frac{7.3 \times 10^{-5} \text{ radians/second}}{(8 \text{ hours} \times 3600 \text{ seconds/hour})}$$

$$\alpha \approx 2.7 \times 10^{-9} \text{ radians/second}^2$$

5. **Calculate the torque (τ):**

$$\tau = I \times \alpha$$

$$\tau = (0.118\,\text{kg} \times \text{m}^2) \times (2.7 \times 10^{-9}\,\text{radians/second}^2)$$

$$\tau \approx 3.2 \times 10^{-11}\,\text{Nm (Newton meters)}$$

Thus, the calculated torque required to rotate the rectangular flat solar plate is approximately **3.2 x 10^(-11) Nm**. To achieve this torque, we will design a spiral spring based on the following calculations.

Figure 2 : Proposed Model

Conclusion

Solar tracking systems offer significantly higher efficiency and performance compared to fixed or stationary solar photovoltaic systems. The primary benefit of these systems is their ability to increase electricity generation, which depends on the solar tracker's geographic location and other factors. However, solar tracking systems have several drawbacks. They are more expensive than fixed systems due to the complexity of the technology involved and the use of costly components for their operations.

Active tracking systems, which rely on optical sensors and microcontroller-based active drives, provide the advantage of high-precision tracking and are widely used. These systems are often preferred over auxiliary bifacial and time-based active drives. However, they share the common limitation of lower efficiency on cloudy days, as the sensors require sunlight to function properly. In contrast, passive drives use the changing physical properties of fluids instead of complex control circuits, motors, gears, and sensors. This simplicity makes passive drives more cost-effective and practical than active systems.

Additionally, several factors influence the energy output of solar tracking systems, including the photovoltaic material, the geographical location of solar irradiances, ambient temperature, weather conditions, the angle of sun incidence, and the orientation of the panels.

Future Work

Future developments in solar tracking systems could focus on enhancing their efficiency. This may involve the integration of advanced tracking algorithms, more precise sensors, and optimized control mechanisms to maximize solar energy capture. Additionally, advancements in materials and manufacturing techniques could lead to the creation of more efficient, lightweight tracking systems. Solar tracking systems can also be integrated with other renewable energy technologies to form hybrid systems. For instance, combining solar tracking with wind turbines or incorporating energy storage solutions can enable better utilization of multiple renewable sources, improving the overall performance and reliability of the system.

Another area for future improvement is reducing the cost of solar tracking systems, making them more affordable and accessible. This could be achieved through innovations in manufacturing processes, component optimization, and the use of more cost-effective materials. Furthermore, increased market demand and economies of scale can help drive down costs.

Future solar tracking systems could be designed for adaptability and flexibility, allowing them to track the sun's position in various weather conditions and environments. Incorporating intelligent control systems that adjust tracking parameters based on weather data, cloud cover, or shading would ensure optimal energy capture regardless of external conditions. Moreover, solar tracking systems could be designed with scalability in mind, allowing easy expansion or integration into existing solar installations. Modular designs would enable the addition of tracking units to boost capacity as needed, making the system suitable for various project sizes.

The future potential of solar tracking systems is vast, offering opportunities to enhance efficiency, integrate with other renewable energy sources, leverage IoT technologies, reduce costs, improve adaptability, and incorporate advanced sensors. These advancements will play a key role in the widespread adoption of solar tracking systems and in the ongoing development of sustainable and efficient solar energy generation.

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