MAXIMIZING SOLAR ENERGY OUTPUT THROUGH AN INTEGRATED SUN TRACKING AND AUTOMATED CLEANING

Jeevan Roj R, Vijayakumar J , Vijayakumar J

Department of Electronics and Instrumentation

Bharathiar University Coimbatore, Tamilnadu, India

Abstract: *Solar energy has become an up-and-coming solution that will help meet the increasing demand for energy worldwide and reduce environmental concerns. However, dust and dirt accumulation on solar panel surfaces can significantly reduce their efficiency, reducing energy output. This study, therefore, looks at how regular cleaning can help maintain the optimal performance and longevity of solar photovoltaic systems. The research project presents a Smart Solar Panel Maintenance System that promotes energy efficiency through integrated Sun tracking and automated cleaning mechanisms. This system uses light-dependent resistors (LDRs) to dynamically vary the orientation of solar panels, resulting in more sunlight absorption throughout the day. It is equipped with an advanced monitoring system designed to assess panel cleanliness; any deviations in terms of energy output indicate that it is time for cleaning. The system is modelled, simulated, and controlled to ensure precise and efficient operation using MATLAB and Simulink. Subsequently, the cleaning mechanism is initiated when energy falls by 10%, 20% or 30%, which is appropriate for each case. For instance, when loss equals 10%, an air blower removes light debris, while a water sprayer is used for a loss of 20%. If there is an energy reduction, which translates into about 10 per cent, then the appropriate action would be to use an air blower to remove light debris. However, a water sprayer will be needed if it is around 20 per cent. A wiper will be good enough where we are talking about losses between thirty percent or even beyond since these are not simple cases anymore. The design covers the insufficiency of regular fixed solar panel installations, maximizing performance while minimizing breakdowns and labour costs. Additionally, incorporating sun tracking and automatic cleaning into the PV system enhances energy generation while reducing operational expenses, increasing solar panels' overall economic and environmental viability. This research is a step forward in renewable energy technologies towards solar power generating systems that are more efficient and dependable.*

Keywords **: Solar panels, Maintenance system, Sun tracking, Automated cleaning, Renewable Energy**

INTRODUCTION

Solar energy is a crucial renewable energy source, which is essential for sustainable development by providing low- cost, low-carbon energy [1]. The importance of photovoltaic (PV) systems, especially solar panels, has increased significantly to become the most cost-effective option for new power generation in many regions globally, thereby significantly reducing electricity generation prices [2]. This growth in global solar power installation has been majorly influenced by a pressing need to meet increasing demands for power, where extensive usage of solar PV technology has been observed compared to concentrated Solar Power (CSP) applications [3]. They are versatile and indispensable as they serve multiple roles, such as producing heat, electricity, and desalinating water [1]. However, research outputs also demonstrate the possibility of maximizing PV power efficiency by optimizing solar tracking systems. This means there are significant improvements in power output efficiency during specific hours of the day, indicating how much solar tracking technology can enhance energy production. Notably, deploying solar tracking systems, whether dual-axis or single- axis, is essential in increasing exposure to sunlight and consequently improving performance without incurring substantial costs [10, 11]. Different research works in this line have focused on new methods and tools used to improve the performance and maintenance of solar panels. Some of these include studies on solar panel cleaning systems, automatic cleaning processes, and innovations in solar panel maintenance, all aimed at making the solar energy landscape more efficient and sustainable [15- 22].

RELATED WORKS

Solar energy has numerous advantages: it can reduce or curb harmful carbon emissions, conserve the environment, and support sustainable development. Transitioning into solar power has the potential for significantly lowering carbon footprints, saving the planet and ensuring a brighter future for generations yet to come. Solar energy can be utilized in diverse areas and seamlessly fits into daily human life, serving as a power source for street lights and household electrical appliances [23]. Silent operation, no greenhouse gas emission characteristics, and renewability make solar panels an eco- friendly alternative energy source [24].

Research works have focused on the importance of solar tracking in optimizing energy output, with various studies indicating the benefits of using tracking systems over static panels, significantly when weather conditions are changing [8-11]. This proposal sparked discussions about establishing a network for inter-city sharing of solar electricity during cloudy periods regarding its viability, transmission distances, which could lead to substantial power losses, and the need for backup systems during unfavourable weather conditions. The idea also looks at whether we could construct large-scale solar farms, such as those in California deserts, which would suffice for national electricity needs. Technical considerations about power transmission efficiency over long distances are given, stressing the importance of minimizing energy losses due to resistance. The literature emphasizes the problematic challenges of cleaning solar panels. These challenges include the adverse effects on panel efficiency. Diverse cleaning systems and techniques are evaluated, including manual techniques, water-based methods, mechanized cleaning solutions, and even new ones involving drones and self- cleaning panels. Seasonal aspects such as dust accumulation, variations in deposit types and concentrations across regions, and the economic viability of cleaning methods are discussed [25].

METHODS

In this research work, sun tracking integrated with solar panel cleaning has been proposed. The block diagram of the proposed system is shown in Fig 1.

A.Data set

Azimuth (True North) is measured in degrees clockwise from north, and it refers to the direction on a compass where the sun is on the horizon: southeast or west. Regarding solar tracking systems, azimuth means the angle between the sun's direction and reference direction (in many cases, true north or true South). For instance, if the azimuth angle is 0°, it points towards true north, while an azimuth angle reading of 180° denotes true South. Solar tracking systems often use sensors or algorithms to keep adjusting positions of solar panels or collectors to trail along with changes in the sun's azimuth angle throughout the day. Solar tracking systems can maximize the captured sunlight by locating the panels perpendicular to the sun's azimuth, thus increasing energy generation. Elevation: The angle between the horizon and the sun is measured vertically. It indicates how high up in the sky from the observer's position. As used here, location means that elevation is usually measured between 0 degrees (horizon) and 90° (directly overhead) at a given point on Earth. Due to Earth's rotation and axial tilt concerning its orbit around the sun, sun elevation changes throughout the day. This implies that solar tracking systems have to modify their panel or collector tilt angle in order for them to match with solar elevation throughout any time of the year for optimized exposure to sunlight. When you get closer to the equator,

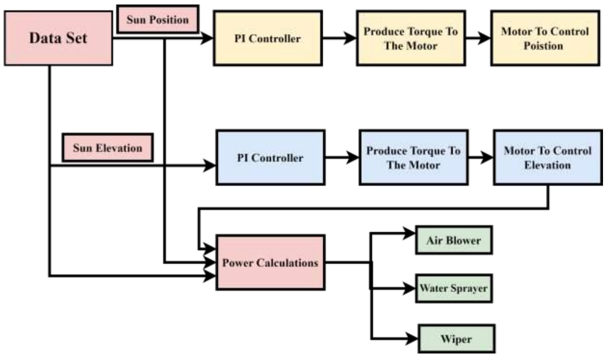


Fig. 1. Block Diagram of Proposed work

higher elevation angles are reached by the sun as compared with regions further away from the equator where the sun's path in the sky is low.

Solar Position Algorithms: These algorithms utilize mathematical models to calculate where precisely the sundial will be found based on inputs such as date, geographic coordinates (latitude and longitude), and clock time. Using these formulas, one can precisely predict from what point on the compass light should fall towards Earth's surface at a particular moment.

Sun trackers: Light-sensing sensors will have to be incorporated into the system to detect the direction and intensity of sunlight. Solar tracking systems could establish real-time sun azimuth and elevation angles by analyzing the sensor's output. These data were used in the proposed work to simulate the sun's position.

A. PI Controller

A Proportional-Integral (PI) controller is a commonly used feedback control system in engineering and automation applications to regulate processes and maintain desired system behaviour. It consists of two basic control strategies: proportional control and integral control.

Proportional Control (P) is based on current error, defined as the difference between the desired setpoint and the actual measured value of the system. The controller output varies linearly with this error. It is represented as:

□(□) = □□ × □(□)   □ □ □

(□) Represents a controller output at time □.

□□ Stands for its proportional gain; it is a tuning parameter determining how fast the controller can respond to an error. Increasing □□ Increases this ability but may cause overshoots and oscillations in an attempt to reduce steady-state errors.

The integral Control (I) mechanism takes care of the error history over time. It integrates the error signal over time and adds a correction proportional to the size and length of the error. This helps wipe out any steady-state error that can still exist if only proportional control is used, especially in systems with non-zero setpoints or steady disturbances. Mathematically, this is represented as:
(□) = □□ × $\int_0$
□□□

□(□)□□

□□ It is the integral gain which determines how fast the integral term accumulates. Increasing □□ Increases the ability of the controller to eliminate steady-state errors but may result in instability or excessive oscillations.A proportional-integral (PI) Controller combines proportional and integral control actions to produce controller output. The output equals the sum of proportional and Integral parts.

$(t) = K_p \times (t) + K_i \times \int_0 (\tau)$
□□□

The proportional term provides immediate correction of changes in the error. In contrast, any remaining steady-state error is gradually reduced by the integral term through the integration of the error over time. The essential advantage of a PI controller is its ability to provide both rapid response to changes in the error (proportional action) and elimination of steady-state error (integral action). However, the PI controller must be well-tuned by adjusting proportional and integral gains to balance speed and response stability correctly.

B. Torque Produced by Motor:

The equation shows the fundamental behaviour of a DC motor.

— □□ represents how quickly current □ flowing through the coil that generates magnetic field changes with time □

□ is the inductance of the coil in the motor.

□ is the voltage applied across terminals.

□□ Represents the torque constant, which tells how much torque a motor unit produces per unit current across it.

□□ Is the motor's back-EMF constant, which describes how much potential difference across its coil a motor produces per unit angular speed (□□).

□ It represents the resistance of an electric coil of the machine.

In this case, □□ dt This means the angular velocity at which the motor shaft is resolving.

T = □□□□□ □□□

□ stands for torque developed by a motor.

□□ It is a torque coefficient of a motor.

□□ The torque constant of a motor describes how to relate the current flowing through it and its generated torque respectively.

□ Electrical current flowing through an armature winding of a motor.

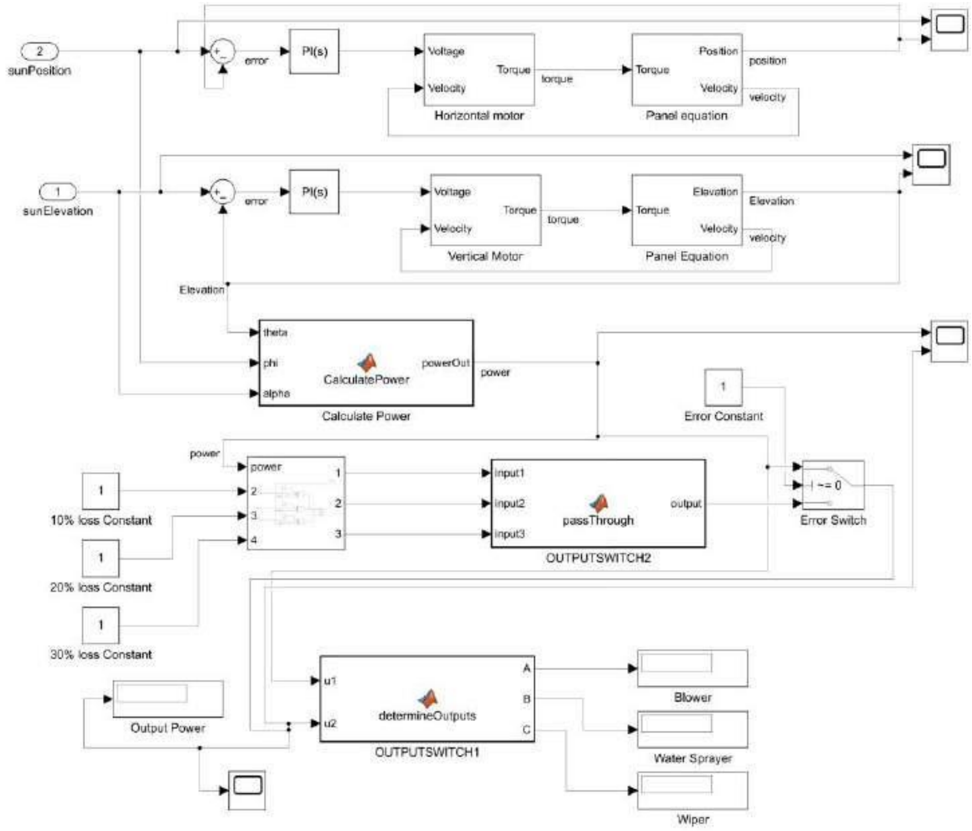
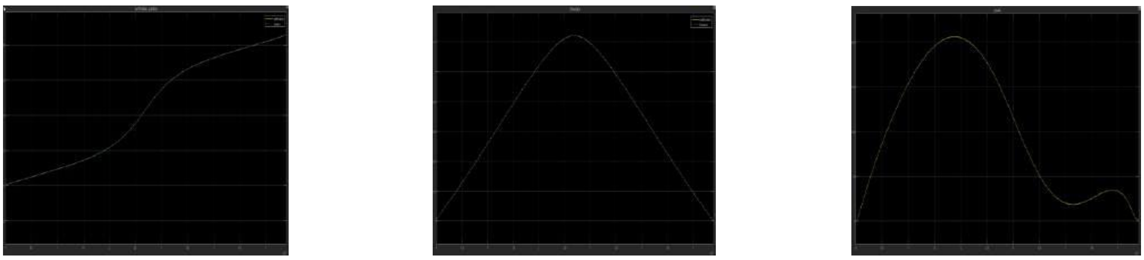


Fig. 2. Proposed Integrated Sun Tracking and Automated Cleaning System



(a) (b) (c)

Fig. 3. Real world data (a) Sun Position (b) Sun Elevation (c) Actual power

However, this depends on their design, as they can provide significant torque.

A. *Motor to Control Proportional Position:*

B. $\frac{d^2\theta}{dt^2} = 1/J(T - K$ □

C. dt

D. Where $\frac{d^2\theta}{d}$

It is the second derivative of angle concerning time □ ; in other words, it represents the solar panel's acceleration. The solar panel's inertia moment is denoted by □. It measures how difficult it is to change an object's rotation motion. The moment of inertia depends on how mass is distributed about the centre of rotation and the object's shape. □ denotes the torque applied to the solar panel. A torque is a force that rotates an object around an axis. The coefficient damping □□ Represents damping in systems or any resistance in motion. It usually involves frictional or other dissipative forces acting in opposition to the movement of the solar panel. The first derivative of time concerning angle, □□,

□□

represents the angular speed of the solar panel or how fast it rotates at a given point in time. The same equation is used in another motor to control the elevation angle.

This equation essentially gives the behaviour of a solar panel system's elevation angle in response to external torques and damping acting on it, expressed in terms of the moment of inertia by □. The solution to this differential equation allows one to see how long the solar panel angles will last and develop control strategies for solar trackers to maximize captured solar energy.

E. ***Power Calculation:***

Power Out of the solar panel is calculated by the below equation

$$power\ Out\ =\ Calculate\ Power\ (theta, phi, alpha, A, beta) \quad (7)$$

The dot product of the incident sun vector with the panel average vector is calculated by.

$$dotprod = (beta) * sin(pi/2 - alpha) * cos(theta - phi) +$$
$$(beta) * cos(pi/2 - alpha) \quad (8)$$

The formula below can calculate direct power out

$$Power\ Out\ =\ 1.353 * 0.7.\wedge(sin(alpha).\wedge - 0.678) * dot\ prod * A *$$
$$0.195 * 1000 \quad (9)$$

1.353 represents a coefficient which remains constant.

0.7 represents a base which remains constant.

$\wedge(sin(alpha).\wedge - 0.678)$ is exponentiation in this portion involves raising.

A represents an input for a given surface area. This entire expression, therefore, calculates direct power based on various parameters present.

$$powerOut\ =\ Math.(powerOut, 0) \quad (10)$$

The above equation guarantees that the calculated power is not less than zero. It replaces any negative values with zeros, indicating that if the sun is behind the panel, then its out power must be zero.

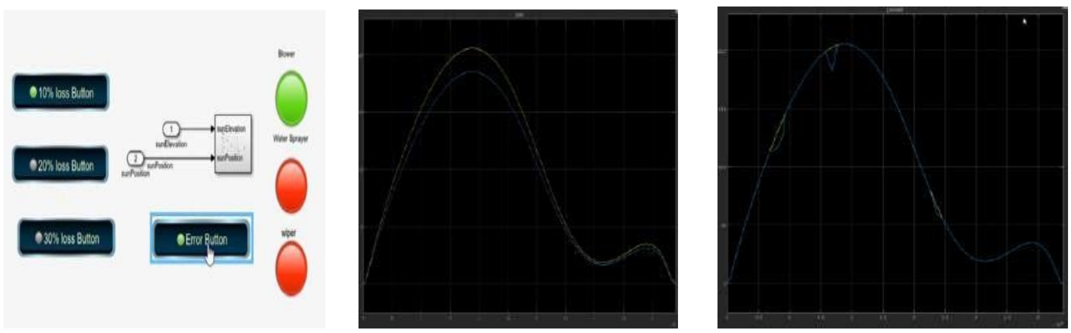


Fig. 4. When power loss is 10% (a) User Interface (b) Actual power vs Loss power (c) Actual power retained after loss

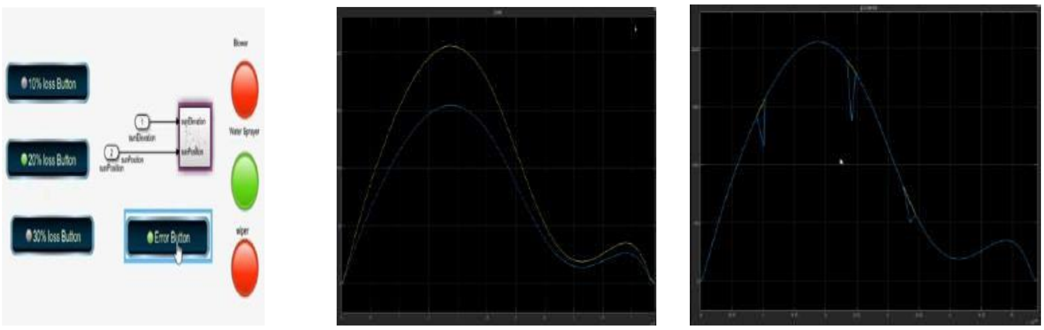


Fig. 5. When power loss is 20% (a) User Interface (b) Actual power vs Loss power (c) Actual power retained after loss

Based on the power loss from the previous reading, the system activates the cleaning process. The system activates an air blower when the solar panel output experiences a 10% loss, a water sprayer at 20%, and a wiper at 30%. The designed program is shown in Fig 2.

RESULTS AND DISCUSSION

The system's dynamics were successfully modelled by simulating the system using the Simulink program. The program accurately represents system behaviour by using different blocks and functions in Simulink; this includes input sources and mathematical operations. Empirical data was compared with the model, and it was found to be based on real-world conditions shown in Fig 3. The results of this study demonstrate that the methodology employed in modelling complex systems with dynamic behaviours is effective, thus offering a platform for further research and development. Cleaning Mechanisms Activation: activating different cleaning mechanisms (air blower, water sprayer, wiper) based on the detected loss in energy output.

A. *Result 1:*

Fig 3 shows how Smart Solar Panel Maintenance System changes its electricity production in the presence of 10% energy loss. The plot graph records the variation in energy output at different time points with a perceptible descent from the desired level. This discrepancy is detected by the monitoring device of this system, which incorporates Light Dependent Resistors (LDRs); it then triggers cleaning action to restore performance to normal levels. The ability to monitor and react instantly like this shows how efficient solar panels can be at their highest capacity, which will prevent wastage of power and enhance the overall efficiency of a system

B. *Result 2:*

The image shows how the Smart Solar Panel Maintenance System detects a deviation of energy output when a 20% reduction in power is recorded. The chart shows the measured energy output over time, which significantly dropped compared to the anticipated output level. In such cases, this variation is detected by the system's complex tracking system using light-dependent resistors (LDRs) that engage the necessary cleaning mechanism. Any significant loss causes it to employ sprinklers to flush out contaminants and restore regular operation. This capability demonstrates real-time monitoring and intervention for maintaining solar panels' efficiency and productivity to reduce energy losses and improve overall system reliability.

C. *Result 3:*

Fig. Decoding And Interpreting The Smart Solar Panel Maintenance System's Energy Deviation At A Loss Of 30 Percent Efficiency: This Figure Shows That A Considerable Variation Exists In The Amount Of Energy Produced By The Smart Solar Panel Maintenance System When The Efficiency Drops By Thirty Percent. The Chart Represents Measured Energy Production Over period Showing A Substantial Decrease From What Was Expected To Be Produced. This deviation is detected, and an appropriate cleaning mechanism is initiated through the system's accurate monitoring technique using LDRs (Light Dependent Resistors). Consequently, to respond to this enormous loss, the system is provided with a wiper that completely removes dirt accumulated for efficient functioning. These real-time monitoring and intervention capabilities underscore how these systems manage losses of this kind in solar panel efficiency. They ensure the generation of constant electricity and abundant system efficacy.

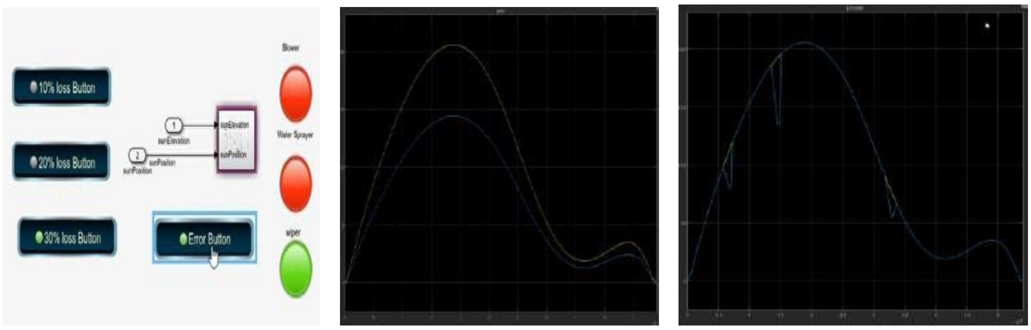


Fig. 6. When power loss is 30% (a) User Interface (b) Actual power vs Loss power (c) Actual power retained after loss

It ensures timely maintenance by detecting energy losses by activating its cleaning mechanisms to maximize energy output and extend solar panel lifespan. This permits the system to decrease manual maintenance requirements and minimize downtime, reducing costs and making solar power more viable as a renewable energy source. In addition, it contributes to less water use and reduced labour requirements, among other environmental benefits, for it to be environmentally sustainable.

CONCLUSION AND FUTURE WORK

This study introduces Integrated Sun Tracking and Automated Cleaning System to enhance solar photovoltaic system's efficiency and reliability. This system ensures optimal energy production by integrating Sun tracking features and automatic cleaning mechanisms that reduce the adverse effects caused by dirt and dust accumulation. MATLAB/Simulink-based modelling and simulation have been used extensively to capture the system's dynamic behaviour, thus proving its practicality. Considering the future impacts of this research on renewable energy, this matter goes way beyond scalability, its applicability in different settings and other future aspects concerning furthering the efficiency of these sources. The results show that the study aids in establishing solar power generators that work better than before as it offers new insights into how to generate more reliable solar power, essential for a transition to sustainable energy globally.

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