Impact Assessment of Rooftop Solar Penetration in Distribution Grid

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Abstract

The rapid adoption of rooftop solar PV systems has boosted decentralized power generation but also introduced challenges such as voltage instability, power quality deterioration, reverse power flow, and grid imbalance. These issues lead to voltage fluctuations, harmonic distortions, and inefficiencies in energy management. This study analyzes the impact of rooftop solar penetration on distribution networks and proposes an integrated solution combining MPPT-based dynamic solar tracking with an automated cleaning mechanism to enhance efficiency. The MPPT system optimally orients panels for maximum solar absorption, improving power output and reducing fluctuations, while the automated cleaning system prevents efficiency losses due to dust accumulation. A hardware prototype has been developed and tested, demonstrating improved power stability, higher energy yield, and reduced intermittency. This integrated approach maximizes rooftop solar utilization while mitigating grid impacts, offering a practical solution for reliable and sustainable distributed solar energy systems.

Keywords: Solar, Solar penetration, tilting of Solar Panels, automatic solar cleaning, MPPT

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1. Introduction

The increasing adoption of rooftop solar photovoltaic (PV) systems has revolutionized decentralized energy generation. However, it also presents challenges such as voltage instability, reverse power flow, and power quality issues within the distribution grid. The intermittent nature of solar energy, influenced by factors like irradiation, temperature variations, and shading, contributes to fluctuations in power output. Additionally, dust accumulation on solar panels significantly reduces their efficiency, leading to performance degradation over time.To address these issues, this project investigates the impact of rooftop solar penetration on the distribution network and proposes an integrated solution to optimize power generation. The approach combines **Maximum Power Point Tracking (MPPT)-based dynamic solar tracking** with an **automated cleaning mechanism** to enhance energy efficiency. The MPPT algorithm continuously adjusts the panel's tilt for maximum sunlight absorption, while the cleaning mechanism prevents dust buildup, ensuring consistent performance.A hardware prototype is designed and tested to evaluate the effectiveness of this system in improving power output, stabilizing voltage levels, and mitigating grid instability. The findings demonstrate that integrating tracking and cleaning mechanisms significantly enhances solar energy utilization while reducing system intermittency. This research provides a practical and scalable solution for optimizing rooftop solar PV performance, supporting sustainable energy integration into existing power infrastructure. By addressing key technical challenges, this project contributes to enhancing the efficiency and reliability of distributed solar energy systems, promoting the broader adoption of clean energy solutions.

2. Related Work

This project reviews prior research on rooftop solar penetration challenges, including power quality, voltage stability, MPPT, solar tracking, and automated cleaning. High solar PV penetration can cause voltage fluctuations, power imbalances, and reverse power flow, affecting grid reliability. While mitigation techniques like reactive power compensation and energy storage exist, they often require costly infrastructure, limiting feasibility for small-scale systems.MPPT algorithms optimize PV output, with methods like Perturb and Observe (P&O) and Incremental Conductance focusing on electrical characteristics. Integrating MPPT with dynamic solar tracking can further enhance energy yield, though practical rooftop implementations remain limited. Additionally, dust accumulation reduces panel efficiency, and while cleaning solutions like robotic or electrostatic systems exist, they often require maintenance or external power.

3. Objectives

The objectives of the project is to examines the impact of rooftop solar PV on the distribution grid and proposes an integrated solution to enhance efficiency and stability. It addresses voltage instability, power quality issues, and reverse power flow by implementing a dynamic solar tracking system with MPPT for optimal energy absorption. An automated cleaning mechanism prevents dust accumulation, ensuring consistent efficiency without manual maintenance. A hardware is made and tested to evaluate improvements in power output, voltage stability, and grid reliability, assessing the feasibility of large-scale adoption for enhanced rooftop solar performance.

4. Problem Statement

The increasing adoption of rooftop solar PV systems promotes renewable energy and reduces reliance on fossil fuels, but their widespread integration also introduces technical challenges, affecting grid stability and power quality.

4.1 Voltage Instability and Power Quality Issues

One of the most critical challenges associated with rooftop solar penetration is voltage instability. Solar PV generation is inherently intermittent, as it depends on varying environmental factors such as solar irradiance, temperature and shading.

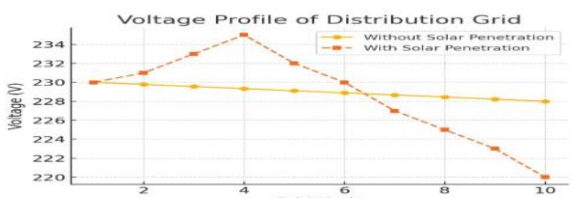

Figure 1: Voltage profile of distribution grid

4.2 Impact of Dust Accumulation on Solar Panel Efficiency

Another major concern affecting solar PV performance is dust accumulation and soiling losses. The efficiency of solar panels is significantly reduced when dirt, dust, and environmental pollutants accumulate on their surfaces, obstructing sunlight absorption.

4.3 Need for an Integrated Optimization Approach

To ensure the efficient and reliable operation of rooftop solar PV systems, it is crucial to address both grid-related challenges and efficiency losses due to soiling. While Maximum Power Point Tracking (MPPT) algorithms help optimize solar energy extraction, their effectiveness can be further enhanced by incorporating a dynamic solar panel positioning mechanism.

The maximum power output of a solar panel is determined using the equation:

$$P_{max} = V_{mp} \times I_{mp}$$

where P_{max} = maximum power output

V_{mp} = voltage at maximum power point

I_{mp} = current at maximum power point

By continuously adjusting the tilt angle, the panel maintains maximum efficiency throughout the day.The net improvement in power output from both MPPT-based tracking and automated cleaning can be expressed as:

$$P_{improved} = P_{base} \times \eta_{tracking} \times \eta_{cleaning}$$

where $P_{improved}$= enhanced power output, P_{base} = base power output without optimization, $\eta_{tracking}$ = efficiency improvement due to tracking, $\eta_{cleaning}$ = efficiency improvement due to cleaning.

5. Methodology

This section describes the approach used to analyze the impact of rooftop solar penetration on the distribution grid and the development of an integrated solution to enhance solar power generation. The methodology involves system design, hardware implementation, and performance evaluation to ensure the effectiveness of the proposed solution.

5.1 Problem Analysis and Data Collection

The analysis of the challenges posed by high rooftop solar penetration, including voltage instability, power quality issues, and reverse power flow is done. Data related to power fluctuations, voltage variations, and solar generation patterns are collected through simulations and real-time monitoring of existing rooftop solar installations. These insights help in understanding how rooftop solar affects grid stability and overall power quality.

5.2 Design of the System

To address the identified challenges, a dual-function system is designed that integrates a solar tracking mechanism and an automated cleaning system. The tracking system adjusts the orientation of the solar panel to maximize sunlight capture, improving efficiency by following the sun’s movement throughout the day. The cleaning system ensures that dust and debris do not accumulate on the panel surface, preventing efficiency loss and maintaining consistent power output.

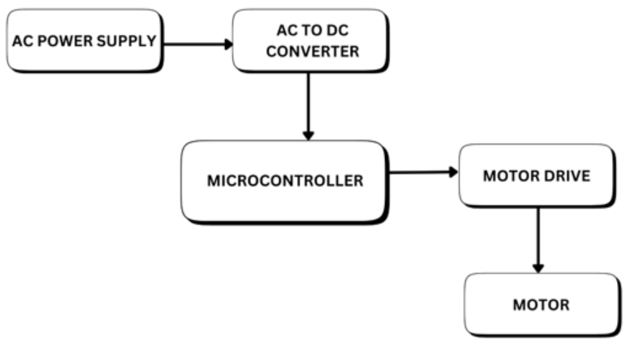

Figure 2: Block diagram of automatic cleaning system for solar panels

This block diagram represents a motor control system powered by an AC power supply. The AC to DC converter converts the AC supply into DC voltage, which powers the microcontroller. The microcontroller processes input signals and controls the motor drive, which regulates the motor's speed and direction. This system is commonly used in automation, robotics, and motorized applications.

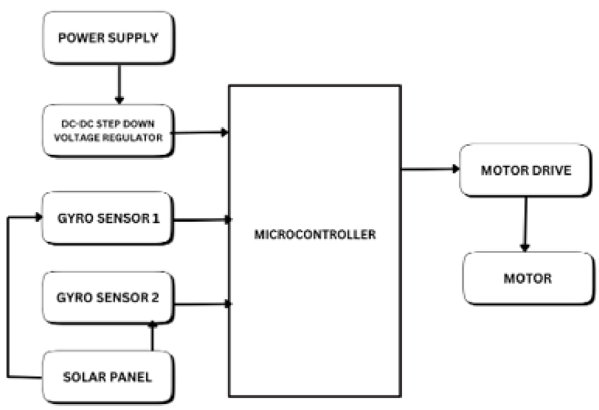

Figure 3: Block diagram of automatic tilt mechanism of solar panels

This block diagram represents a solar tracking system controlled by a microcontroller. The power supply is regulated by a DC-DC step-down voltage regulator to provide a stable voltage for the system. Gyro sensors (Gyro Sensor 1 and Gyro Sensor 2) detect the orientation of the solar panel, sending data to the microcontroller. Based on this input, the microcontroller adjusts the panel’s position by controlling a motor drive that moves the motor, ensuring optimal sunlight absorption. This system enhances solar energy efficiency by dynamically adjusting the panel's angle.

5.3 Simulation Diagram

This circuit diagram represents a microcontroller-based motor control system with wireless communication. It includes a motor driver (L298N) to control the motor, a DC-DC buck converter (LM2596) for voltage regulation, and a gyroscope sensor for motion detection. The system is powered by a regulated DC supply for stable operation.

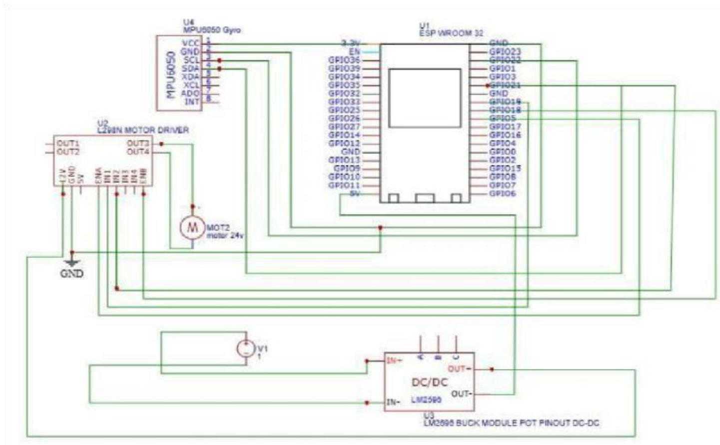

Figure 4: Simulation diagram of automatic tilt mechanism of solar panels

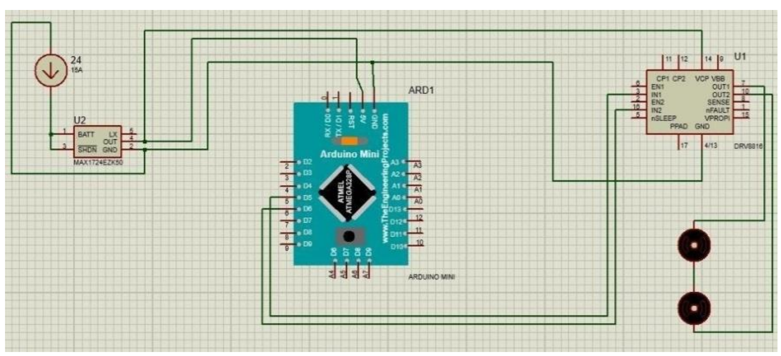

Figure 5: Simulation diagram of automatic cleaning system for solar panels

This circuit features an Arduino Mini as the central controller, interfacing with a motor driver module to control two motors. A 24V power source supplies energy, regulated for system components. The setup is ideal for automation or robotics applications, where Arduino processes inputs and drives motors accordingly for precise control.

5.4 Performance Evaluation

The system is validated by analyzing power output, efficiency retention, and grid stability. Experimental data assess the impact of solar tracking on energy capture and the cleaning system on efficiency loss. Voltage stability and harmonic distortions are also measured to ensure power quality.

Figure 6: Comparison of power output with and without tilting

6. Conclusion

This project tackles the challenges of high rooftop solar penetration, including voltage instability and power quality issues, by developing a dual-function system with solar tracking and automated cleaning. Experimental results confirm that dynamic tracking boosts power generation by optimizing panel orientation, while automated cleaning prevents dust buildup, maintaining efficiency. By enhancing solar output and grid stability, this scalable solution mitigates the negative effects of high solar penetration. Future research can refine these mechanisms for greater energy efficiency and cost-effectiveness, supporting large-scale adoption. This project improves rooftop solar efficiency through automated tracking and cleaning, ensuring higher energy output and grid stability. It promotes renewable energy adoption, reduces carbon emissions, and lowers maintenance costs. By supporting sustainable development, it makes solar power more accessible, affordable, and reliable, benefiting both communities and the environment.

7. References

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