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ANALYSIS OF DUST ACCUMULATION EFFECTS ON SOLAR PV PERFORMANCE WITH AN OPTIMIZED CLEANING STRATEGY: EXPERIMENTAL AND IoT-BASED APPROACH

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Abstract - *Dust accumulation on solar photovoltaic (PV) modules is a critical environmental factor that significantly degrades system performance, particularly in regions with high particulate matter. This study presents a comprehensive analysis of dust-induced performance deterioration and proposes an optimized cleaning strategy using an integrated experimental and Internet of Things (IoT)-based approach. A controlled experimental setup was developed to evaluate PV output under clean, naturally dusted, and artificially dusted conditions. Key electrical parameters, including voltage, current, and power, were measured alongside environmental variables such as solar irradiance and temperature. An IoT-based monitoring system was implemented to enable real-time data acquisition and remote performance tracking. The results demonstrate that dust accumulation leads to a substantial reduction in power output (approximately 15–20%) and efficiency due to decreased solar irradiance reaching the PV cells. Time-series analysis reveals a progressive degradation pattern, with higher sensitivity during the initial stages of dust deposition. Based on experimental data, an adaptive cleaning strategy was developed using a threshold-based and cost–benefit optimization model. The proposed approach identifies an optimal cleaning interval that minimizes energy loss while reducing maintenance costs. Validation results indicate significant improvement in system efficiency and overall energy yield compared to conventional fixed cleaning schedules. The study highlights the effectiveness of combining IoT-based monitoring with data-driven optimization for enhancing PV system performance and sustainability.*

Key Words: Solar Photovoltaic, Dust Accumulation, IoT Monitoring, Cleaning Optimization, Performance Degradation, Renewable Energy

1. INTRODUCTION

1.1 Background

The global energy sector is undergoing a significant transition from fossil-fuel-based generation to renewable energy systems due to concerns over climate change, resource depletion, and environmental sustainability. Among renewable sources, solar photovoltaic (PV) technology has emerged as one of the most promising solutions because of its scalability, decreasing installation costs, and minimal environmental impact during operation. As solar PV deployment increases worldwide, maintaining high system efficiency becomes essential to ensure optimal energy yield and economic viability. However, real-world PV performance is strongly influenced by environmental conditions, particularly dust accumulation, which is recognized as a major degradation factor in many regions. Dust deposition reduces solar irradiance reaching the PV cells, thereby limiting power generation and overall efficiency, making it a critical issue for sustainable PV operation (Mani and Pillai, 2015).

1.2 Problem Statement

Despite advancements in PV technology, a significant gap persists between theoretical and actual system performance due to environmental factors. Under real operating conditions, dust accumulation leads to a noticeable decline in output power, primarily by reducing the short-circuit current and shifting the maximum power point. Conventional maintenance practices, such as periodic manual cleaning, are typically based on fixed schedules and do not account for real-time system conditions. This results in either excessive cleaning, increasing operational costs, or insufficient cleaning, causing prolonged efficiency losses. Consequently, there is a need for more intelligent and adaptive maintenance strategies that can respond dynamically to environmental variations and system performance degradation (Kimber et al., 2016).

1.3 Research Gap

Although extensive research has been conducted on dust effects and PV performance degradation, several limitations remain in existing studies. Most prior work focuses either on experimental analysis or theoretical modeling without integrating real-time monitoring systems. Additionally, conventional cleaning strategies lack adaptability and are not optimized based on actual performance data. The integration of Internet of Things (IoT) technology in PV systems has shown potential for real-time monitoring; however, its application in developing adaptive cleaning strategies remains limited. Furthermore, there is a lack of comprehensive frameworks that combine experimental validation, IoT-based data acquisition, and optimization techniques to address dust-related losses effectively (Ilse et al., 2018).

1.4 Objectives and Contributions

This research aims to bridge the identified gaps by providing a comprehensive framework for analyzing and mitigating dust-induced performance degradation in PV systems. The study experimentally quantifies the impact of dust accumulation on key electrical parameters such as voltage, current, and power output under different conditions. An IoT-based monitoring system is developed to enable real-time data acquisition and performance tracking. Based on the collected data, an optimized cleaning strategy is formulated using a threshold-based and cost–benefit approach. The proposed methodology is validated through comparative analysis, demonstrating improved efficiency and reduced operational costs. The integration of experimental, monitoring, and optimization techniques represents a significant contribution toward intelligent and sustainable PV system management (Sayyah et al., 2015).

2. LITERATURE REVIEW

2.1 Dust Impact on PV Performance

Dust accumulation on PV panels affects system performance primarily through optical and electrical mechanisms. From an optical perspective, the dust layer causes reflection, scattering, and absorption of incident solar radiation, thereby reducing the effective irradiance reaching the photovoltaic cells. This attenuation directly impacts the photoelectric conversion process. Electrically, the reduction in irradiance leads to a decrease in short-circuit current (Isc), while voltage remains relatively less affected. As a result, the maximum power output of the PV system declines significantly. In severe cases, non-uniform dust deposition can cause partial shading, leading to mismatch losses and hotspot formation, which further degrade system reliability (Jiang et al., 2015).

2.2 Experimental and Field Studies

Experimental and field-based studies have been widely conducted to evaluate the impact of dust on PV performance under controlled and real-world conditions. Laboratory experiments provide precise control over dust density and environmental variables, allowing accurate quantification of performance degradation. In contrast, field studies capture real-time variations in environmental conditions such as wind, humidity, and rainfall, offering more realistic insights. Comparative analysis of these studies indicates that efficiency losses due to dust accumulation typically range between 5% and 40%, depending on factors such as dust composition, exposure duration, and geographical location. These findings highlight the importance of site-specific analysis for effective maintenance planning (Sarver et al., 2017).

2.3 Cleaning Techniques

Various cleaning techniques have been developed to mitigate dust accumulation on PV panels, each with its advantages and limitations. Manual cleaning is the most commonly used method due to its simplicity, but it is labor-intensive and inefficient for large-scale installations. Automated cleaning systems, including robotic cleaners and mechanical brushes, offer improved consistency and reduced human effort but involve higher initial costs. Advanced cleaning technologies, such as electrostatic dust removal and self-cleaning coatings, aim to minimize water usage and maintenance frequency. While these methods show promise, their practical implementation requires further evaluation in terms of cost-effectiveness and long-term performance (Mazumder et al., 2018).

2.4 Optimization Approaches

Optimization of cleaning strategies has gained significant attention as a means to balance energy recovery and maintenance cost. Traditional fixed cleaning schedules are simple but often inefficient, as they do not reflect actual dust accumulation levels. Adaptive cleaning strategies, on the other hand, rely on real-time performance indicators to determine optimal cleaning intervals. Economic models are commonly used to minimize total cost by considering both energy loss and cleaning expenses. Recently, machine learning approaches have been introduced to predict dust accumulation trends and optimize maintenance schedules dynamically. These approaches improve decision-making and enhance overall system efficiency (Ilse et al., 2018).

2.5 IoT-Based PV Monitoring

The integration of IoT technology in PV systems has enabled advanced monitoring and maintenance capabilities. Sensor-based monitoring systems collect real-time data on key parameters such as irradiance, temperature, and power output, providing continuous insights into system performance. This data is transmitted to cloud platforms for analysis and visualization, allowing remote monitoring and diagnostics. IoT-based systems also support smart maintenance by enabling condition-based cleaning and fault detection. The combination of real-time data acquisition and intelligent analytics enhances system reliability, reduces downtime, and supports the development of adaptive maintenance strategies for improved PV performance (Kumar et al., 2019).

3. SYSTEM DESCRIPTION AND METHODOLOGY

3.1 Overall Research Framework

The overall research framework of this study is designed to systematically evaluate the impact of dust accumulation on solar photovoltaic (PV) performance and to develop an optimized cleaning strategy. The methodology follows a sequential flow comprising experimentation, data acquisition, analysis, and optimization. Initially, controlled and real-world experiments are conducted to generate reliable performance data under different dust conditions. This is followed by IoT-based data acquisition, where environmental and electrical parameters are continuously monitored in real time. The collected data is then processed using analytical techniques to quantify performance degradation and identify trends. Finally, an optimization stage is implemented to determine the most effective cleaning interval based on technical and economic considerations. This structured approach ensures logical progression from problem identification to solution development and validation.

3.2 Experimental Setup

The experimental setup is designed to replicate practical operating conditions while maintaining sufficient control for accurate measurement. A crystalline silicon PV module is used, typically rated between 100–250 W, and mounted at an optimal tilt angle corresponding to the local latitude to maximize solar exposure. The system is connected to a measurement unit or resistive load to enable stable recording of electrical parameters.

Three distinct test conditions are considered to evaluate the effect of dust accumulation. The clean panel condition serves as a reference case, representing maximum achievable performance without any surface contamination. The natural dust condition involves exposing the PV module to ambient environmental conditions over time, allowing dust to accumulate organically, thereby reflecting real-world operation. The artificial dust condition is created by applying a controlled amount of dust uniformly on the panel surface, enabling repeatable experiments and precise quantification of performance degradation. These conditions provide a comprehensive understanding of both short-term and long-term dust effects on PV systems.

3.3 Dust Deposition Methodology

The dust deposition methodology combines both natural and controlled approaches to capture realistic and repeatable behavior. In natural accumulation, the PV module is exposed to the environment for a defined duration without cleaning, allowing airborne particles to settle on the surface. This approach captures actual environmental influences such as wind, humidity, and particulate concentration.

In controlled dust application, a known quantity of dust is uniformly distributed on the panel surface, typically measured in grams per square meter (g/m^2). This allows systematic investigation of the relationship between dust density and performance loss. Additionally, dust characterization is performed to understand its physical properties, including particle size, density, and composition. These characteristics influence optical attenuation and adhesion behavior, thereby affecting the extent of performance degradation. The combination of natural and artificial methods ensures both realism and experimental accuracy.

3.4 IoT-Based Monitoring System

3.4.1 Hardware Architecture

The IoT-based monitoring system forms the core of real-time data acquisition and system analysis. It consists of a microcontroller unit, such as ESP32 or Arduino, interfaced with multiple sensors to measure environmental and electrical parameters. Irradiance sensors (e.g., pyranometers or LDR-based devices) are used to measure incident solar radiation, while temperature sensors monitor ambient and module temperatures. Dust sensors, typically based on optical or particulate matter detection principles, provide an estimate of airborne dust concentration. The microcontroller processes sensor data and prepares it for transmission, enabling continuous monitoring of PV system performance.

3.4.2 Communication and Cloud Layer

The communication layer facilitates the transmission of data from the hardware system to remote servers. Wireless technologies such as Wi-Fi or GSM are used depending on network availability and system requirements. The collected data is transmitted to a cloud platform, where it is stored, processed, and visualized. Cloud-based dashboards provide graphical representations of parameters such as irradiance, temperature, and power output, allowing users to monitor system performance remotely. This layer enhances accessibility and enables data-driven decision-making without requiring physical presence at the installation site.

3.4.3 Data Acquisition

The data acquisition process involves continuous sampling and recording of sensor data at predefined intervals, typically ranging from a few seconds to several minutes. A suitable sampling rate is selected to balance data resolution and storage requirements. Real-time logging ensures that temporal variations in environmental conditions and system performance are accurately captured. The recorded data is time-stamped and synchronized across all parameters, enabling precise correlation analysis. This continuous data stream forms the basis for performance evaluation, trend analysis, and optimization of cleaning strategies.

3.5 Performance Measurement

Performance measurement is essential for quantifying the impact of dust on PV systems. The primary electrical parameters measured include voltage (V), current (I), and power (P), where power is calculated as the product of voltage and current. These parameters are recorded under varying environmental and dust conditions.

In addition to basic measurements, I–V and P–V characteristics are analyzed to understand the operational behavior of the PV module. Dust accumulation primarily affects the short-circuit current, leading to a downward shift in the I–V curve and a reduction in maximum power point. Efficiency is calculated as the ratio of electrical output power to incident solar power, providing a key performance indicator for system evaluation. These measurements enable accurate assessment of performance degradation and recovery after cleaning.

4. DATA ANALYSIS AND MODELING

4.1 Comparative Analysis

Comparative analysis is conducted to evaluate the difference in performance between clean and dusted PV panels under similar environmental conditions. By keeping irradiance and temperature as constant as possible, the effect of dust is isolated. This analysis highlights the reduction in current, power, and efficiency due to dust accumulation. The results provide a direct measure of performance degradation and serve as a baseline for further analysis and optimization.

4.2 Time-Series Analysis

Time-series analysis is used to study the variation of PV performance over time as dust accumulates on the panel surface. Continuous data collected through the IoT system allows tracking of parameters such as power output and efficiency on a daily basis. The analysis reveals a gradual decline in performance with increasing exposure duration, indicating cumulative effects of dust deposition. This approach helps in identifying degradation trends and determining the rate at which cleaning becomes necessary.

4.3 Dust Density vs Power Loss Model

The relationship between dust density and power loss is established using controlled experimental data. By applying known quantities of dust (in g/m^2) and measuring the corresponding power output, a functional relationship is derived between dust accumulation and efficiency reduction. The results typically show a non-linear trend, where initial dust deposition causes significant performance loss, followed by a relatively slower degradation at higher dust levels. This model is critical for developing optimized cleaning strategies, as it helps determine the threshold at which cleaning becomes economically and technically justified.

5. OPTIMIZATION OF CLEANING STRATEGY

5.1 Problem Formulation

The optimization of cleaning strategy in solar photovoltaic (PV) systems is formulated as a cost minimization problem, where the objective is to reduce the total operational cost associated with dust accumulation. The total cost is defined as the sum of energy loss due to reduced PV output and the cost incurred for cleaning activities. Energy loss represents the economic impact of decreased power generation caused by dust deposition, while cleaning cost includes labor, water usage, and maintenance expenses. The challenge lies in determining the optimal balance between these two competing factors, as frequent cleaning reduces energy loss but increases operational cost, whereas infrequent cleaning lowers maintenance cost but leads to higher energy losses. Therefore, an optimal solution is required to minimize the combined cost while maintaining efficient system performance.

5.2 Cleaning Threshold Determination

A critical step in the optimization process is the determination of an appropriate cleaning threshold based on system performance degradation. In this study, a threshold is defined in terms of efficiency drop, where cleaning is triggered once the PV system efficiency decreases by approximately 10% from its clean-state value. This threshold is selected based on experimental observations indicating that beyond this point, the rate of energy loss becomes significant and economically unfavorable. By using a performance-based threshold instead of a fixed time interval, the cleaning process becomes adaptive and responsive to actual environmental conditions. This approach ensures that cleaning is performed only when necessary, thereby improving both technical efficiency and cost-effectiveness.

5.3 Cost–Benefit Analysis

Cost–benefit analysis is conducted to evaluate the trade-off between cleaning frequency and total operational cost. Different cleaning intervals, such as short (e.g., 3 days), moderate (e.g., 7 days), and long (e.g., 15 days), are analyzed by calculating the corresponding energy loss and cleaning cost. Short intervals result in minimal energy loss but higher cleaning expenses, while long intervals reduce cleaning cost but lead to significant power loss. The analysis reveals that a moderate cleaning interval provides the most balanced outcome, minimizing the total cost. This demonstrates that neither extreme frequent nor infrequent cleaning is optimal, and an intermediate interval based on system conditions offers the best performance in terms of economic efficiency.

5.4 Proposed Adaptive Cleaning Algorithm

An adaptive cleaning algorithm is developed to automate the decision-making process based on real-time system data. The algorithm takes input from the IoT-based monitoring system, including parameters such as power output, efficiency, irradiance, and dust level indicators. These inputs are continuously analyzed to detect performance degradation. When the efficiency drop exceeds the predefined threshold, the algorithm generates a cleaning trigger signal. This condition-based approach ensures that cleaning actions are aligned with actual system requirements rather than predefined schedules. The algorithm enhances operational efficiency by reducing unnecessary maintenance while ensuring timely intervention to prevent excessive energy loss, thereby improving overall system reliability and sustainability.

6. RESULTS AND DISCUSSION

6.1 Experimental Results

The experimental results clearly demonstrate the significant impact of dust accumulation on PV system performance. Comparative analysis between clean and dusted conditions shows a noticeable reduction in power output, typically in the range of 15–20%, depending on dust density and exposure duration. Similarly, efficiency decreases substantially due to reduced solar irradiance reaching the PV cells. These results confirm that dust acts as a major barrier to effective energy conversion and highlight the necessity of implementing efficient cleaning strategies to maintain optimal system performance.

6.2 I–V and P–V Analysis

The analysis of current–voltage (I–V) and power–voltage (P–V) characteristics provides deeper insight into the electrical behavior of PV modules under dust conditions. Dust accumulation primarily affects the short-circuit current, causing a downward shift in the I–V curve, while the open-circuit voltage remains relatively stable. As a result, the P–V curve exhibits a reduced peak, indicating a lower maximum power point. This shift confirms that dust predominantly impacts current generation, leading to decreased power output and overall efficiency degradation.

6.3 Time-Series Results

Time-series analysis of PV performance reveals a progressive degradation trend as dust accumulates over time. Continuous monitoring shows that power output gradually declines with increasing exposure duration, with more pronounced losses observed during the initial stages of dust deposition. This cumulative effect highlights the importance of timely cleaning, as delayed maintenance can lead to significant energy losses. The time-series data also helps in identifying the rate of degradation, which is essential for determining optimal cleaning intervals.

6.4 IoT System Performance

The IoT-based monitoring system demonstrates high accuracy and reliability in capturing real-time PV performance data. Validation against manual measurements indicates that the system maintains an error margin of less than 5%, which is acceptable for practical applications. Additionally, the system enables continuous monitoring and remote access to performance data through cloud-based platforms. This real-time capability allows for early detection of performance degradation and supports data-driven decision-making for maintenance and optimization.

6.5 Optimization Results

The implementation of the optimized cleaning strategy yields significant improvements in PV system performance. The analysis identifies an optimal cleaning interval of approximately 7 days under the studied environmental conditions. This interval effectively balances energy recovery and maintenance cost. After applying the optimized strategy, a noticeable improvement in efficiency and power output is observed, along with a reduction in overall operational cost. These results validate the effectiveness of the proposed approach and demonstrate its potential for practical implementation in dust-prone regions.

7. CONCLUSION

This study presented a comprehensive analysis of the impact of dust accumulation on solar photovoltaic (PV) system performance and proposed an optimized cleaning strategy using an integrated experimental and IoT-based approach. The results clearly demonstrate that dust deposition significantly reduces PV efficiency and power output by limiting the amount of solar irradiance reaching the module surface. Experimental observations indicated a notable decline in performance, with power loss in the range of 15–20% and corresponding efficiency reduction under dusted conditions. The analysis of I–V and P–V characteristics further confirmed that dust primarily affects the short-circuit current, leading to a lower maximum power point.

The implementation of an IoT-based monitoring system enabled continuous, real-time data acquisition of key environmental and electrical parameters with acceptable accuracy. This facilitated detailed time-series analysis, revealing a progressive degradation trend due to dust accumulation. Based on these findings, a threshold-based adaptive cleaning strategy was developed, incorporating cost–benefit analysis to determine the optimal cleaning interval. The results identified an optimal interval of approximately 7 days, which effectively balances energy recovery and maintenance cost.

Validation of the proposed approach demonstrated significant improvement in system efficiency and output performance compared to conventional fixed cleaning schedules. Overall, the integration of experimental validation, IoT-based monitoring, and optimization techniques provides a reliable and practical solution for enhancing PV system efficiency, particularly in dust-prone environments.

8. FUTURE SCOPE

Future research can focus on extending this work through long-term and multi-seasonal studies to capture the effects of varying climatic conditions on dust accumulation and PV performance. The integration of advanced machine learning and artificial intelligence techniques can further enhance predictive maintenance by forecasting dust deposition trends and dynamically optimizing cleaning schedules. Additionally, incorporating automated cleaning technologies such as robotic or electrostatic systems with IoT-based decision frameworks can enable fully autonomous PV maintenance. Further investigation into detailed dust characterization, including chemical composition and particle morphology, can improve understanding of soiling mechanisms. Expanding the study to large-scale grid-connected PV systems and integrating it with smart grid infrastructure will also enhance its practical applicability and contribute to more efficient and sustainable energy management systems.

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