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EVALUATION OF DEGRADATION MECHANISM IN FIELD-AGED SILICON PV MODULES VIA IV CHARACTERIZATION AND INFRARED THERMOGRAPHY

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ABSTRACT

The long-term performance and reliability of silicon photovoltaic (PV) modules are influenced by environmental and operational stress factors, leading to gradual degradation in field conditions. This study investigates the degradation mechanisms in field-aged crystalline silicon PV modules through a combined diagnostic approach using current–voltage (I–V) characterization and infrared (IR) thermography. Electrical performance was analyzed by measuring key parameters such as open-circuit voltage (Voc), short-circuit current (Isc), fill factor (FF), series resistance (Rs), shunt resistance (Rsh), and maximum power output (Pmax). Deviations from manufacturer specifications provided quantitative insights into electrical degradation, including increased resistive losses, current mismatch, and junction deterioration. Infrared thermography was employed to identify localized thermal anomalies, including hot spots, micro-cracks, interconnect failures, and shading effects. Correlation between electrical and thermal diagnostics enabled the identification of dominant degradation mechanisms affecting module performance. The study confirms that series resistance increases and shunt resistance reduction are primary contributors to performance loss, while thermal anomalies reveal the spatial localisation of defects. The combined methodology proves to be a reliable and non-destructive approach for assessing degradation, facilitating preventive maintenance and lifetime estimation. The findings contribute to an improved understanding of field-induced degradation in silicon PV modules, thereby enhancing the reliability and operational efficiency of photovoltaic systems under real environmental conditions.

Keywords: *Field-aged PV modules[1], I–V characterization[2], infrared thermography[3], degradation mechanisms[4], series resistance[5]*

1. INTRODUCTION

The growing demand for clean and sustainable energy has accelerated the deployment of photovoltaic (PV) systems worldwide. Among the available PV technologies, crystalline silicon photovoltaic modules dominate the global market due to their high conversion efficiency, long service life, and technological reliability. Although these modules are designed for extended outdoor operation, their performance gradually deteriorates when exposed to real field conditions. Understanding the degradation mechanisms in field-aged silicon PV modules is therefore essential for maintaining system efficiency and ensuring long-term operational reliability. Field-deployed PV modules are continuously subjected to environmental and operational stresses such as temperature cycling, humidity, ultraviolet radiation, dust accumulation, and mechanical loading. These factors initiate various physical and electrical degradation processes within the module components, including solar cells, encapsulant layers, and electrical interconnections. As a result, the electrical performance of PV modules declines over time, leading to reduced power output and efficiency. Current–voltage (I–V) characterization is a widely used technique for assessing the electrical health of PV modules. It provides essential parameters such as short-circuit current, open-circuit voltage, fill factor, and maximum power output, which serve as indicators of performance degradation. However, I–V analysis alone does not reveal the spatial distribution or physical origin of defects. Infrared thermography is a non-destructive diagnostic method that enables visualization of surface temperature variations in operating PV modules. Localized temperature rise, commonly known as hot spots, is often associated with internal defects such as cell cracks, degraded interconnections, and resistive losses. By integrating I–V characterization with infrared thermography, a comprehensive evaluation of degradation mechanisms becomes possible. This combined approach enhances the accuracy of fault identification and provides valuable insights into the condition of field-aged silicon PV modules

2. LITERATURE REVIEW

Long-term operation of silicon photovoltaic (PV) modules in outdoor environments leads to gradual performance degradation, which has been widely examined in photovoltaic research. Earlier investigations mainly relied on current–voltage (I–V) characterization to assess electrical degradation in field-aged PV modules. These studies reported a continuous decline in power output and fill factor, primarily attributed to increased series resistance and reduced shunt resistance. Degradation sources such as corrosion of metallic contacts, solder joint deterioration, cell micro-cracking, and junction defects were identified as key contributors to electrical performance loss in crystalline silicon modules operating under real environmental conditions. In recent years, non-destructive diagnostic techniques have gained significant attention for identifying degradation mechanisms in PV modules. Infrared (IR) thermography has been extensively applied to monitor temperature distribution across operating PV modules. Research findings indicate that localized temperature elevations, commonly referred to as hot spots, are closely associated with internal defects such as cracked cells, degraded interconnections, shading effects, and resistive losses. Infrared thermography enables rapid and contactless inspection, making it particularly suitable for in-situ field analysis. However, several studies have highlighted that thermal imaging alone does not provide quantitative information regarding electrical performance degradation and is sensitive to external environmental conditions. Consequently, recent research emphasizes the combined use of I–V characterization and infrared thermography to achieve a more reliable evaluation of degradation mechanisms. By correlating electrical parameter changes with thermal anomalies, researchers have demonstrated improved accuracy in fault identification. Despite these advancements, comprehensive field-based studies on aged silicon PV modules remain limited, highlighting the need for further integrated diagnostic investigations.

3. METHODOLOGY

The present study focuses on evaluating degradation mechanisms in field-aged crystalline silicon photovoltaic (PV) modules using a combined approach of electrical and thermal diagnostics. Commercial silicon PV modules that had been in outdoor operation for several years were selected from an installed photovoltaic system. The modules were visually inspected to identify apparent defects such as discoloration, delamination, or physical damage before detailed measurements were conducted. Electrical performance assessment was carried out through current–voltage (I–V) characterization under natural sunlight conditions. A portable I–V tracer was used to record the I–V and P–V curves of the selected PV modules at near-standard operating conditions. Key electrical parameters including short-circuit current, open-circuit voltage, maximum power output, fill factor, series resistance, and shunt resistance were extracted from the measured curves. The obtained values were compared with manufacturer-rated specifications to estimate performance degradation. Infrared thermographic analysis was performed on the same modules under steady irradiance conditions using a calibrated thermal imaging camera. Thermal images were captured during module operation to observe temperature distribution across the module surface. Regions exhibiting abnormal temperature rise were identified as potential hot spots and correlated with possible internal defects. Finally, results from I–V characterization and infrared thermography were jointly analyzed to establish a relationship between electrical degradation and thermal anomalies. This integrated diagnostic approach enabled reliable identification of dominant degradation mechanisms in field-aged silicon PV modules.

4. RESULT

The electrical and thermal performance of field-aged silicon photovoltaic (PV) modules was evaluated using I–V characterization and infrared thermography. I–V measurements revealed a noticeable reduction in the maximum power output of the aged modules when compared with manufacturer-rated specifications. A decline in fill factor was consistently observed, indicating increased internal losses within the modules. The short-circuit current showed moderate reduction, whereas the open-circuit voltage exhibited comparatively smaller variation, suggesting degradation primarily associated with resistive losses rather than junction failure. Analysis of extracted electrical parameters showed an increase in series resistance and a decrease in shunt resistance in several modules. These changes are indicative of degraded interconnections, solder joint fatigue, and the presence of micro-cracks within the solar cells. Variations in power loss among different modules reflected non-uniform aging under field operating conditions. Infrared thermographic imaging revealed non-uniform temperature distribution across the module surfaces. Localized hot spots with elevated temperatures were detected in specific regions of the modules during operation. These thermal anomalies were predominantly observed near cell edges and interconnect regions, suggesting localized resistive heating. Modules exhibiting higher temperature rise generally corresponded to those showing greater electrical performance degradation. A clear correlation was established between electrical degradation identified through I–V characterization and thermal anomalies detected via infrared thermography. The combined results confirm that integrating electrical and thermal diagnostics provides a more reliable assessment of degradation mechanisms in field-aged silicon PV modules compared to individual techniques.

5. DISCUSSION

The results obtained from the combined electrical and thermal analysis provide important insights into the degradation behavior of field-aged silicon photovoltaic (PV) modules. The observed reduction in maximum power output and fill factor indicates significant performance deterioration due to long-term exposure to outdoor environmental conditions. The relatively smaller change in open-circuit voltage compared to short-circuit current and fill factor suggests that degradation is mainly associated with resistive losses rather than severe junction damage. The increase in series resistance identified through I–V characterization can be attributed to degradation of metallic interconnections, solder joint fatigue, and corrosion effects arising from prolonged humidity and temperature cycling. Similarly, the reduction in shunt resistance indicates the presence of leakage paths caused by cell micro-cracks, encapsulant degradation, or junction defects. These electrical changes are consistent with degradation mechanisms commonly reported in aged crystalline silicon PV modules operating under real field conditions. Infrared thermographic analysis further supports these findings by revealing localized temperature elevations across the module surfaces. The presence of hot spots indicates regions of increased resistive heating, which are often linked to cracked cells, degraded interconnects, or localized shading. Modules exhibiting pronounced thermal anomalies were found to correspond with higher electrical performance loss, demonstrating a strong relationship between thermal and electrical degradation. The integration of I–V characterization with infrared thermography proved effective in identifying dominant degradation mechanisms. This combined approach enables both quantitative performance evaluation and spatial defect localization, offering a more comprehensive assessment of PV module health compared to individual diagnostic techniques.

6. CONCLUSION

This study presented an integrated assessment of degradation mechanisms in field-aged silicon photovoltaic (PV) modules using current–voltage (I–V) characterization and infrared thermography. The results demonstrated that prolonged outdoor exposure leads to noticeable deterioration in electrical performance, primarily reflected through reduced maximum power output and fill factor. The observed increase in series resistance and decrease in shunt resistance indicate the presence of resistive losses, degraded interconnections, and cell-level defects within the aged modules. Infrared thermographic analysis revealed non-uniform temperature distribution across module surfaces, with localized hot spots indicating regions of elevated resistive heating. These thermal anomalies were closely associated with electrical performance degradation, confirming that temperature variations serve as reliable indicators of underlying defects. The strong correlation between I–V parameter degradation and thermal patterns highlights the effectiveness of combining electrical and thermal diagnostics for accurate fault identification. The integrated diagnostic approach adopted in this study provides a comprehensive understanding of degradation behavior by linking performance loss with physical defect locations. This methodology offers significant advantages over individual techniques by enabling reliable condition monitoring of photovoltaic systems under real field conditions. The findings of this research contribute to improved assessment strategies for aged silicon PV modules and can assist in enhancing maintenance planning, system reliability, and long-term performance of photovoltaic installations.

7. REFERENCE

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