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AI-Driven MPPT Optimization for Perovskite-Based Flexible Solar PV Panels in Partial Shading Conditions

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ABSTRACT

The integration of artificial intelligence (AI) into Maximum Power Point Tracking (MPPT) systems has emerged as a transformative solution for enhancing energy efficiency in perovskite-based flexible solar photovoltaic (PV) panels, particularly under partial shading conditions. This study explores the design, implementation, and evaluation of AI-driven MPPT techniques tailored for dynamic urban environments. Fabricated using advanced perovskite materials and encapsulated for flexibility and durability, these panels exhibit high power conversion efficiency and adaptability to non-traditional surfaces. Comparative analyses reveal that AI-based MPPT outperforms conventional methods in tracking accuracy, response time, and energy yield. The findings underscore the scalability and robustness of AI-driven systems, highlighting their potential for urban applications such as rooftop PV installations, solar-integrated windows, and portable solar devices. The study concludes that AI-enhanced MPPT systems significantly improve the viability of solar energy solutions in environments with non-uniform illumination, paving the way for sustainable urban energy infrastructures.

Keywords: Maximum Power Point Tracking, Solar PV, Artificial Intelligence, partial shading condition

INTRODUCTION

The increasing demand for sustainable and efficient energy solutions has elevated the role of solar photovoltaic (PV) technology, particularly in urban environments where space constraints necessitate innovative designs [1]. Flexible solar PV panels, especially those based on perovskite materials, have emerged as a promising solution due to their lightweight, adaptable form factors, and high-power conversion efficiency [2]. These panels can be seamlessly integrated into non-traditional surfaces such as building facades, rooftops, and even wearable devices, making them ideal for urban applications [3,4]. However, one of the primary challenges facing solar PV systems in urban settings is the prevalence of partial shading caused by obstacles such as buildings, trees, and other structures. Partial shading can significantly impact the energy harvesting efficiency of solar PV panels by creating non-uniform illumination, which leads to localized hotspots and reduces the overall power output. The effects of partial shading are especially pronounced in flexible PV systems, which are often installed in configurations that increase their exposure to shading [5]. Maximum Power Point Tracking (MPPT) algorithms are crucial for optimizing the energy output of solar PV systems under varying environmental conditions. Conventional MPPT techniques, such as Perturb and Observe (P&O) and Incremental Conductance (IC), perform well in uniform illumination scenarios. However, they often struggle with rapidly changing shading conditions, which are common in urban settings [5,6]. These traditional algorithms may fail to identify the global maximum power point (MPP) on the PV panel's characteristic curve, instead converging on local maxima that limit energy efficiency [7,8]. Given the

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dynamic nature of partial shading, there is a pressing need for more adaptive and intelligent MPPT solutions that can quickly and accurately track the global MPP to maximize energy harvesting [9,10]. Artificial intelligence (AI)-driven MPPT methods, leveraging machine learning and optimization algorithms, have shown promise in addressing these limitations by providing real-time adaptability and superior accuracy compared to conventional approaches [9,10]. This study aims to showcase the effectiveness of AI-driven MPPT techniques in optimizing energy yield from perovskite-based flexible solar photovoltaic (PV) panels under partial shading conditions. By harnessing advanced AI algorithms in combination with the unique properties of perovskite materials, the research focuses on enhancing the adaptability of MPPT systems to dynamic shading scenarios, thereby maximizing energy output in environments with non-uniform illumination. Furthermore, the study provides practical insights into the integration of AI-driven MPPT in urban energy systems, contributing to the broader adoption and efficiency of renewable energy technologies.

METHODOLOGY

This study employs a narrative review methodology to evaluate the effectiveness of AI-driven MPPT systems for perovskite-based flexible solar PV panels under partial shading conditions. The methodology synthesizes information from scientific literature, experimental studies, and computational analyses, focusing on three key areas: Material Science: The fabrication process of perovskite PV panels, including material selection, deposition techniques, and performance metrics. AI Algorithms: The implementation of neural networks, convolutional neural networks (CNNs), and reinforcement learning for real-time MPPT optimization under diverse shading patterns. Performance Metrics: Evaluation of energy yield, tracking efficiency, and adaptability of AI-driven MPPT systems in dynamic environments, informed by controlled experiments and real-world data.

Material Preparation Procedures

These are the procedures to follow when preparing your materials for effective Maximum Power Point (MPP) tracking techniques.

Fabrication of Perovskite-Based Flexible PV Panels

The fabrication of perovskite-based flexible PV panels involves the utilization of organic-inorganic hybrid perovskite materials due to their excellent optoelectronic properties and mechanical flexibility [11]. The process begins with the synthesis of the perovskite material, typically a combination of lead halide and organic cations, followed by deposition techniques such as spin-coating, blade-coating, or inkjet printing onto a flexible substrate like polyethene terephthalate (PET) or polyethene naphthalate (PEN). Subsequent annealing processes ensure crystallinity and uniformity [12,13]. To enhance flexibility and durability, encapsulation layers are applied to protect against environmental factors, with metrics such as bending radius and mechanical fatigue tests used to evaluate flexibility and resilience.

Design of AI-Driven MPPT System

The AI-driven MPPT system is designed to optimize energy extraction under varying illumination conditions, leveraging advanced machine learning techniques. The core algorithm employs models such as neural networks, CNNs, or reinforcement learning, trained to identify and adapt to the maximum power point under partial shading scenarios [14,15]. A training dataset is generated through a combination of simulation and experimental data, covering diverse shading patterns, incident angles, and irradiance levels. This dataset enables the AI model to learn the relationship between shading patterns and optimal operating points [16-25]. Real-time implementation integrates sensors for voltage and current measurements, with the AI model continuously updating control signals to optimize energy output [16].

Experimental Setup

The experimental setup involves testing the performance of the fabricated PV panels and the AI-driven MPPT system under both controlled and real-world conditions. Controlled tests are conducted using programmable light sources to simulate partial shading patterns, while real-world experiments are carried out in outdoor environments with natural shading variations [19-26]. Key performance metrics include: Energy Yield: Total energy harvested over a defined period, compared to theoretical maximums. Tracking Efficiency: Ratio of the power tracked by the MPPT system to the actual maximum power available. Response Time: Time taken by the MPPT system to converge to the maximum power point after a change in shading conditions. High-resolution data acquisition systems record electrical parameters and environmental conditions, ensuring comprehensive analysis. The results provide insights

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into the efficacy and practicality of integrating AI-driven MPPT techniques with perovskite-based flexible PV panels in dynamic environments [17,18,20].

Performance Comparison

AI-driven Maximum Power Point Tracking methods demonstrate a significant improvement over conventional techniques, such as Perturb and Observe (P&O) and Incremental Conductance (IC), under identical operating conditions [27,8]]. A comparative analysis reveals that:
Efficiency: AI algorithms, particularly those utilizing machine learning models like neural networks and reinforcement learning, achieve higher efficiency in identifying the Maximum Power Point. In controlled experiments, AI-driven MPPT exhibited a 15-25% increase in energy output compared to P&O and IC methods during rapid irradiance changes [29,5].
Response Time: AI-driven systems adapt to variations in solar irradiance and temperature approximately 40% faster than traditional MPPT approaches. This speed is critical for maintaining optimal energy harvesting, especially in dynamic weather conditions [30,6]
Accuracy: AI techniques achieve near-optimal tracking precision, maintaining the operating point closer to the true MPP under fluctuating conditions. This minimizes energy losses caused by oscillations around the MPP [31,15].

Adaptability

AI-driven MPPT methods excel in adapting to complex and dynamic shading patterns, a common challenge in real-world solar PV installations. Key findings include:
Predictive Capabilities: Machine learning models, trained on historical irradiance and shading data, predict shading events and adjust the operating point preemptively. This leads to sustained energy extraction even under partial shading conditions [16].
Robustness: AI-based systems dynamically adjust to non-uniform irradiance distributions caused by shading from buildings, trees, or clouds. Unlike conventional methods, which struggle under such conditions, AI-driven MPPT maintains a stable performance, extracting 10-18% more energy from shaded modules [15].
Scalability: These methods are scalable to larger systems with multiple interconnected PV arrays, further enhancing their adaptability to varied shading scenarios [17].

Implications for Urban Applications

The superior performance and adaptability of AI-driven MPPT present transformative opportunities for urban solar energy systems. The implications are as follows: Rooftop PV Systems: AI-powered MPPT enhances the energy output of rooftop installations by optimizing energy capture under partial shading and varying sunlight angles caused by nearby structures. This translates to maximized energy efficiency and improved return on investment for urban settings with limited rooftop space [31-35]. Solar-Integrated Windows: The ability of AI systems to operate efficiently under low-light and dynamic shading conditions makes them ideal for solar-integrated windows. These technologies rely on capturing diffuse sunlight, where AI-driven optimization ensures sustained performance [36-41]. Portable Solar Applications: For portable solar devices often exposed to inconsistent sunlight, AI-driven MPPT provides robust tracking, ensuring reliable energy supply for applications such as outdoor activities, emergency response, and portable electronics [42-51]. The integration of AI into MPPT systems not only enhances energy efficiency but also broadens the applicability of solar PV technology to complex and dynamic environments [52-59]. These advancements pave the way for more resilient and versatile urban solar energy solutions.

Findings of the Study

Performance Improvement: AI-driven MPPT systems achieve a 15-25% increase in energy yield and a 40% faster response time compared to conventional methods like Perturb and Observe (P&O) and Incremental Conductance (IC). Adaptability: These systems demonstrate robust performance under complex shading patterns, maintaining 10-18% higher energy output in partially shaded scenarios. Predictive models further enhance energy capture by preemptively adjusting to shading variations. Urban Applications: AI-driven MPPT systems optimize energy capture for rooftop PV installations, solar-integrated windows, and portable devices, ensuring efficiency in limited space and low-light conditions.

CONCLUSION

The integration of AI into MPPT systems for perovskite-based flexible solar PV panels addresses the critical challenge of partial shading, enhancing energy efficiency and adaptability in dynamic urban environments. AI-driven solutions not only outperform conventional MPPT methods but also

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broaden the applicability of solar technologies to varied contexts, including building facades, wearable devices, and portable applications. These advancements represent a significant step toward sustainable and resilient urban energy systems, aligning with global goals for renewable energy adoption. Further research is recommended to refine AI models and expand their scalability across diverse PV technologies and environmental conditions.

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