Development and Validation of Novel Fault Detection Algorithms for Deployed PV Systems

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ABSTRACT

The global photovoltaic (PV) capacity has witnessed exponential growth in recent years, primarily driven by the widespread deployment of grid-connected PV (GCPV) systems. Ensuring the efficiency, safety, and reliability of these systems necessitates robust fault detection and analysis mechanisms. This paper presents the outcomes of a research study focused on designing novel fault detection algorithms and assessing their effectiveness across multiple existing PV installations. The study also includes an empirical evaluation of the algorithms' real-world performance. A key contribution of this work is the formulation of PV fault detection methods utilizing two critical indicators: the power ratio (PR) and the voltage ratio (VR). These indicators serve as the basis for identifying different types of faults occurring at the PV module level, within PV strings, or in the maximum power point tracking (MPPT) unit.

Key words- Photovoltaic System, grid connected photovoltaic, maximum power point tracking

1. INTRODUCTION

This paper presents an analysis of fault detection in photovoltaic (PV) arrays using a fuzzy logic-based approach. The fuzzy logic system operates using three primary input parameters: the percentage of voltage drop (PVD), percentage of open-circuit voltage (POCV), and percentage of short-circuit current (PSCC). To enhance the precision of fault identification in PV systems, the fuzzy logic model is integrated with power and voltage ratio algorithms, resulting in an overall detection accuracy of up to 99.12%. The fuzzy logic systems were evaluated through testing and were observed to deliver consistent and identical performance outcomes.

The primary aim of this study is to showcase the research conducted on the design and implementation of innovative fault detection and degradation analysis techniques for photovoltaic (PV) systems. Fault detection algorithms in PV systems have been extensively utilized to identify a variety of issues occurring in PV installations. These algorithms typically rely on key electrical parameters such as voltage, current, power, and the series resistance of PV modules, as well as environmental factors like ambient temperature and solar irradiance. However, these parameters are not always readily available at PV sites, which creates a need to enhance current fault detection approaches to function effectively using a reduced set of PV and environmental parameters [1]. In this research, data was primarily analyzed

through controlled laboratory experiments, without the benefit of real-time, long-term data from field-deployed PV modules across different geographic locations. The first component of this work outlines the creation of several PV fault detection algorithms, which are categorized into three main types: (1) mathematical and statistical methods, (2) fuzzy logic-based fault detection systems, and (3) artificial neural network (ANN)-based models. Notably, all these approaches primarily depend on two core indicators — power ratio and voltage ratio — for detecting faults within PV arrays. The second significant contribution of this work is the proposal of a novel technique for mitigating hot spots in PV modules [2]. As noted by R. Hariharan et al. [1], abnormal conditions such as faults and partial shading can significantly reduce the maximum power output from PV arrays. Therefore, identifying these issues is essential for improving system reliability and efficiency. According to H. Imanshu et al. [2], solar photovoltaic energy remains an underutilized resource, highlighting the need for further advancements to enhance system performance and dependability. Additionally, M. N. Akram et al. [3] developed a model that characterizes the current-voltage relationship of a solar cell in both the power generation and breakdown regions under positive and negative bias conditions. In another study, M. N. Akram et al. [4] identified three critical failure types in PV arrays: ground faults, line-to-line faults, and arc-related faults.

1.1 PHOTOVOLTAIC ENERGY SYSTEM

Maximum power is extracted from a photovoltaic (PV) system when its internal resistance matches the resistance of the connected load. This condition is typically achieved using a DC-DC power converter, which operates in conjunction with a specific maximum power point tracking (MPPT) algorithm. The converter maintains the system's operation at the maximum power point (MPP) by adjusting and regulating either the voltage or the current accordingly.

2. FAULTS DETECTION

Photovoltaic (PV) energy has emerged as a leading renewable energy source, with the global installed capacity reaching around 75 GW by 2023 enough to meet approximately 1.8% of the world's total electricity demand.

1	China	34,5 GW
2	USA	14,7 GW
3	Japan	8,6 GW
4	India	4 GW
5	UK	2 GW
6	Germany	1,5 GW
7	Korea	0,9 GW
8	Australia	0,8 GW
9	Philippines	0,8 GW
10	Chile	0,7 GW

Figure 1: Top 10 countries in 2024 for annual installed PV capacity

As illustrated in Figure 1, the United Kingdom ranks fifth globally in terms of annual photovoltaic (PV) capacity installations. The rapid expansion of the PV sector has significantly driven down the cost of PV modules [3]. Based on the annual reports from the UK Department for Business, Energy & Industrial Strategy, most PV systems installed are sub-4 kW retrofitted units. The number of such installations rose by 35,188 during 2023, reaching a cumulative total of 836,014 by the end of 2024. This increase in installations contributed an additional capacity of approximately 82 MW.

In photovoltaic (PV) systems, fault detection, analysis, and protection play a critical role in avoiding unforeseen issues. Although PV systems have no moving components and generally require minimal maintenance, they are still prone to faults or failures in components such as PV arrays, power conditioning units, batteries, wiring, and grid connections. Due to their modular and scalable nature, PV systems can be expanded into large-scale power plants by linking multiple PV modules in various array configurations. However, once interconnected, a fault in any single module can negatively impact the performance of the entire system.

In large-scale PV systems, identifying faults can be increasingly challenging, and some issues may go undetected until they cause significant system failure. Faults within PV arrays have, in some cases, led to serious safety concerns, including fire hazards. For instance, on the afternoon of April 5, 2009, smoke was observed coming from the roof of a store in Bakersfield, California, which housed a 383 kW PV system [4]. Furthermore, if a return path exists within the source-circuit conductors, a 30 kW PV array can potentially produce around 100 amps of current—sufficient to cause conductor overheating or even combustion [5].

On the off chance that the PV framework is utilized as a part of conjunction with another force source like a wind or diesel generator then it falls under the class of half breed frameworks.

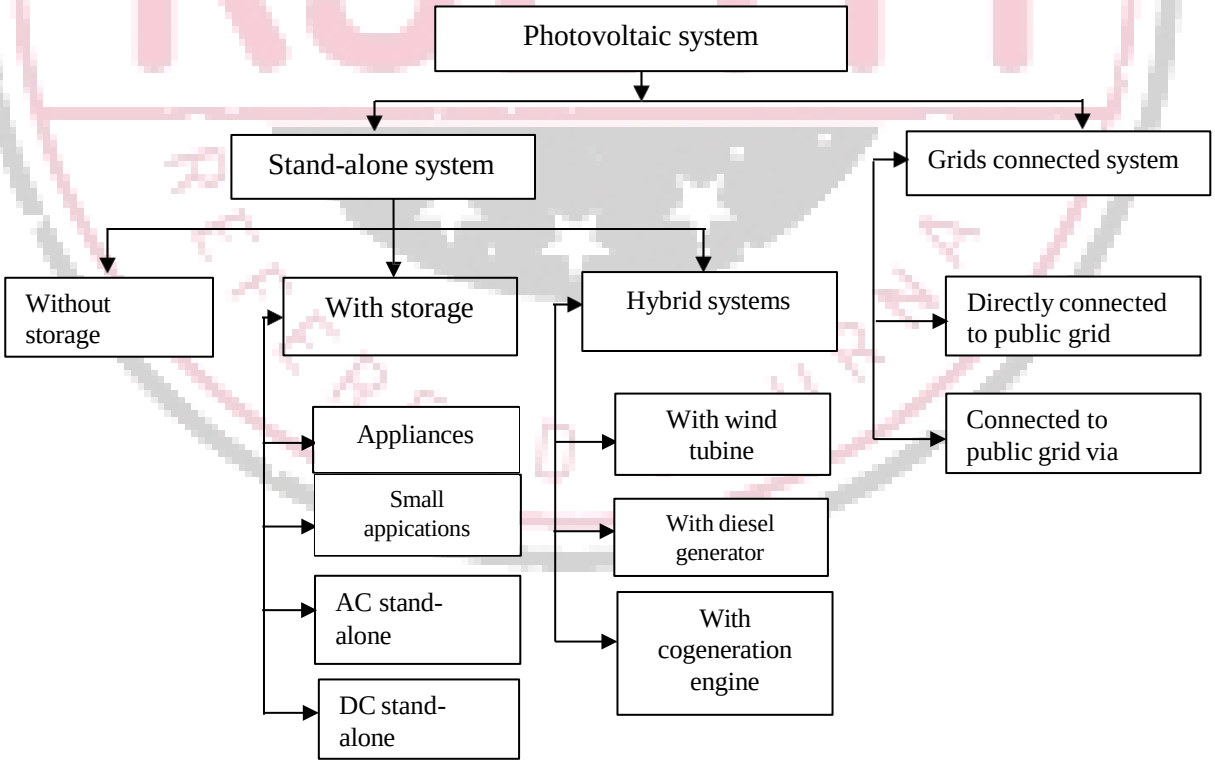

Figure 2: Classification of Solar photovoltaic systems

3. IMPLEMENTED METHODOLOGY

The growing demand for energy requires utilities to increase electricity generation. To address the challenges associated with conventional fossil fuel-based power production, renewable energy sources are being increasingly integrated into the energy mix. Among these, solar energy stands out as a promising alternative. A key advantage of photovoltaic (PV) systems is their ability to harness the sun's abundant and free energy. Through the photovoltaic effect, sunlight is directly converted into clean electrical power. Despite their growing adoption, PV systems still face significant challenges, particularly due to their relatively high initial cost and lower efficiency compared to some other renewable technologies. Additionally, the non-linear characteristics of PV systems can cause fluctuations in output power, potentially resulting in suboptimal performance. These issues, however, can be mitigated by advancements in PV cell manufacturing to reduce costs, along with the development of more efficient power conditioning systems. In recent years, considerable research has been dedicated to enhancing power conditioning technologies to improve their performance. To optimize the total power output of solar PV systems, each module must operate at its maximum power point (MPP), and the associated converters should be designed to achieve high conversion efficiency.

Pulse Width Modulation (PWM) signals are periodic pulse sequences applied to the gates of switching devices to control the operation of power converters. These signals maintain a constant frequency and amplitude, while the pulse width is adjustable based on a modulation signal. Each PWM cycle consists of a consistent voltage level, with the width of each pulse varying according to the input control signal from cycle to cycle. When a PWM signal is applied to the gate of a power transistor, it causes the transistor to switch on and off in response to the pulse width, effectively controlling the converter's operation from one cycle to the next. For effective performance, the frequency of the PWM signal must be significantly higher than that of the modulating signal. This ensures that the average power delivered to the load is governed primarily by the modulating (control) signal. Voltage regulation at the output is achieved through the adjustment of the pulse width—commonly referred to as pulse width modulation. The MATLAB simulation model developed for this study is illustrated in Figure 3.

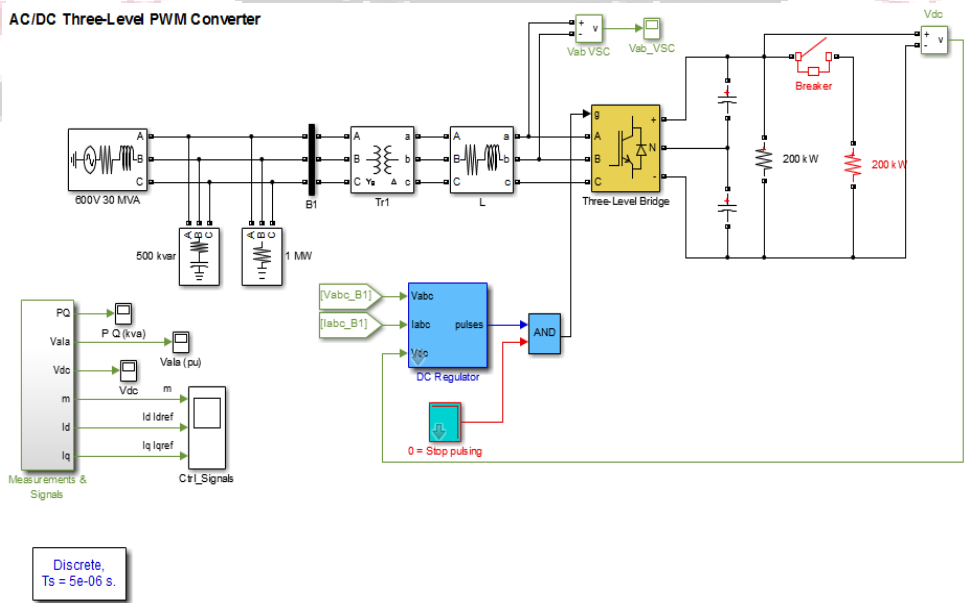

Figure 3: MATLAB Simulink Model of AC/DC Three Level PWM Converter

The photovoltaic cell output voltage is basically a function of the photocurrent which is mainly determined by load current depending on the solar irradiation level during the operation.

$$V_c = (A * k * T_c / e) \ln((I_{ph} + I_0 - I_c) / I_0) - R_S * I_c \quad (5.1)$$

The symbols used are Vc: cell output voltage, V.

Tc: reference cell operating temperature (20 °C).

Rs: series resistance of cell (0.001 Ω).

Iph: photocurrent, function of irradiation level and junction temperature (5 A).

I0: reverse saturation current of the diode (2*10-4 A).

Ic: cell output current

k: Boltzmann constant (1.38 × 10-23 J/K).

e: electron charge (1.602 × 10^-19 C).

For accurate modeling of the solar panel, two diode circuits could have been used. But our scope of study is limited to single diode model. Following are the ideal characteristics of a solar array which show the variation of current and voltage with respect to voltage which are given in Figure 4.

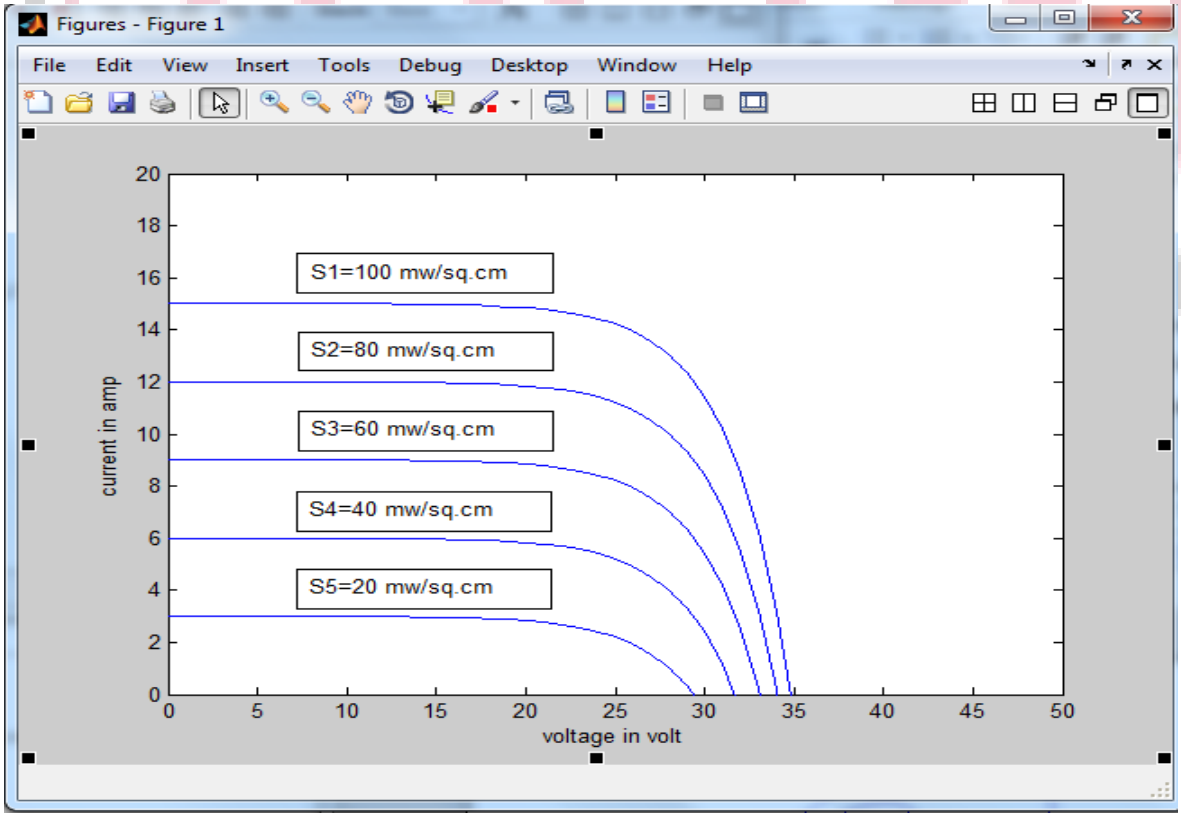

Figure 4: I-V characteristics for different insolation values

A solar photovoltaic (PV) cell generates direct current (DC) electricity, where the output current is influenced by the cell's surface area and the intensity of incident sunlight. Each individual silicon cell typically produces a voltage of approximately 0.5V. To achieve a practical voltage level, multiple cells are connected in series to form a PV module. Maximum power is delivered when the load resistance matches the internal resistance of the PV system, which defines the operating point. This optimal power point is generally achieved using a DC-DC converter equipped with a maximum power point tracking (MPPT) algorithm. The converter maintains operation at the MPP by dynamically adjusting either the output current or voltage.

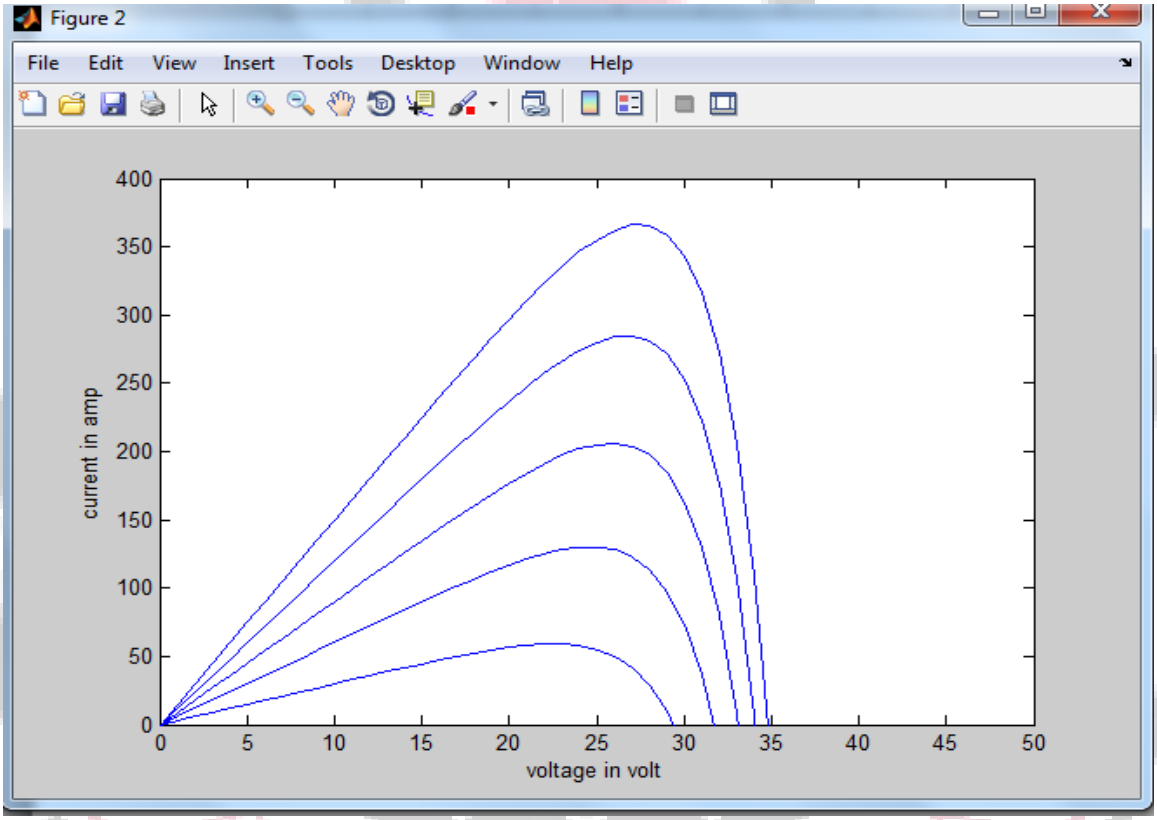

Figure 5: P-V characteristics for different insolation values

The type of power switching component—such as an IGBT, GTO, MOSFET, or an ideal switch—as well as the number of arms (one, two, or three), can be selected through the dialog box. When an ideal switch is chosen, the Three-Level Bridge block functions as a three-level topology using ideal switches for the bridge configuration.

4. RESULTS

As illustrated in Table 1, the maximum power output has been evaluated for both the proposed bypass diode-based PV array algorithm and the existing method. The analysis of the results indicates that the bypass diode-based approach delivers improved performance compared to the previous algorithm. Specifically, the proposed method achieves a maximum power output of 3685 units from the PV array.

Figure 6 presents a graphical representation of the performance of the proposed method in terms of maximum power

output. From this illustration, it is evident that the bypass diode-based PV array algorithm outperforms the previous approach. The comparison highlights that the proposed configuration consistently generates higher power across various partial shading conditions.

Table 1: Comparison of power generated in previous algorithm and proposed configuration for different shading conditions

Reference	Different Shading Condition	Maximum Power	Total Power	Power Improvement (%)
Previous Algorithm et al. [1]	Side and Wide	3097	4000	71.42
	Long and Wide	2696	4000	67.4
	Short and Narrow	3565	4000	89.125
	Long and Narrow	3227	4000	80.675
Proposed	By pass Diode	3685	4000	92.125

Figure 6 shows the graphical illustration of the performance of proposed method discussed in this research work in term of maximum power. From the above graphical representation it can be inferred that the proposed By-pass diode based PV array algorithm gives the best performance for PV array.

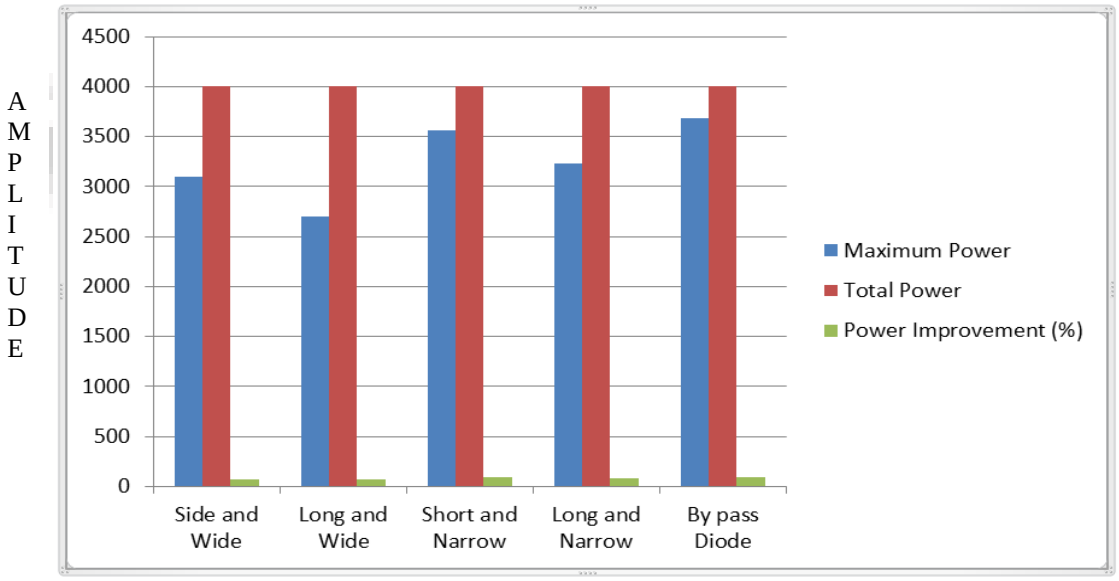

Figure 6: Maximum power for Different shading condition for PV array

5. CONSLUSION

In the present scenario, rising energy demands and environmental concerns have highlighted the need for sustainable alternatives to conventional energy sources. Among these, solar energy stands out due to its abundant availability. Photovoltaic (PV) arrays can effectively harness solar energy for electricity generation. However, the efficiency of solar panels is influenced by several factors, including temperature, the angle of sunlight, solar intensity, and the current-voltage (I-V) operating point. To enhance the steady-state performance and power conversion efficiency of PV systems, various control strategies—such as Zero Voltage Switching (ZVS), Zero Current Switching (ZCS), and Chaotic PWM—have been applied in Cuk converter-based solar PV systems. Experimental analysis of ripple content

for each method revealed that chaotic PWM control significantly reduced output voltage ripples and improved the spectral characteristics of the system. Furthermore, the proposed design contributes to improving energy efficiency when integrated with advanced algorithms, such as those based on neural networks. A mathematical model incorporating a double-diode PV array was developed to achieve maximum power extraction. In addition, the design and implementation of a DC-DC converter, specifically a Cuk converter, demonstrated improved overall efficiency.

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