

A Comprehensive Review of Photovoltaic Array Characteristics and Global Maximum Power Point Localization under Partial Shading Conditions.

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Abstract: *Photovoltaic (PV) arrays exhibit significant performance variations under non-uniform irradiance and changing environmental conditions. Partial shading conditions (PSC) cause electrical mismatch among interconnected PV modules, resulting in substantial power losses. The activation of bypass diodes under PSC further modifies the electrical characteristics of the PV array. Consequently, the conventional single-peak P–V characteristic changes into a multi-peak characteristic consisting of several local maximum power points (LMPPs) and one global maximum power point (GMPP). The number, magnitude, and location of these power peaks depend strongly on shading severity, spatial distribution, array configuration, irradiance, and temperature. Existing studies have investigated individual shading patterns and PV configurations; however, a comprehensive characterization covering diverse operating conditions remains limited. Therefore, this study systematically investigates the I–V and P–V characteristics of PV arrays under representative partial shading patterns and varying irradiance and temperature conditions. The formation, distribution, and localization of LMPPs and GMPP are quantitatively analyzed using key electrical parameters such as voltage, current, and power. The study further establishes the relationship between shading patterns, electrical mismatch, bypass diode operation, and multi-peak characteristics. The resulting characterization provides a systematic knowledge base for developing a robust and efficient GMPPT technique capable of accurately identifying and tracking the GMPP under complex operating conditions.*

Keywords: *Photovoltaic Array, Partial Shading Conditions, I–V Characteristics, P–V Characteristics, Local Maximum Power Point, Global Maximum Power Point, Non-Uniform Irradiance, Electrical Mismatch, GMPP Localization, PV Performance.*

1. INTRODUCTION

Photovoltaic (PV) energy has emerged as a promising renewable energy source due to its clean, sustainable, and decentralized nature. The electrical characteristics of PV modules and arrays are strongly influenced by solar irradiance and operating temperature. Under uniform irradiance, a PV array generally exhibits a nonlinear current–voltage (I–V) and power voltage (P–V) characteristic with a single maximum power point (MPP). However, practical PV installations are frequently subjected to non-uniform irradiance caused by clouds, trees, buildings, dust, and other environmental factors. Such conditions result in **partial shading conditions (PSC)** and introduce electrical mismatch among the interconnected PV modules. The mismatch becomes more significant in series-connected configurations, where the current is constrained by the shaded modules. The activation of bypass diodes helps protect shaded modules from excessive reverse bias and hot-spot formation, but also modifies the overall electrical characteristics of the PV array.

Consequently, multiple peaks can appear in the P–V characteristic, consisting of several **local maximum power points (LMPPs)** and a single **global maximum power point (GMPP)**. The number, magnitude, and location of these power peaks depend on the severity and spatial distribution of shading across the PV array. Different shading patterns, such as row, column, diagonal, random, short-wide, and long-narrow configurations, can therefore produce significantly

different I–V and P–V characteristics. Furthermore, variations in solar irradiance and temperature continuously alter the current, voltage, and power associated with these operating points. Accurate identification and localization of the GMPP consequently become challenging under rapidly changing environmental and shading conditions. A detailed characterization of these electrical behaviors is essential for understanding the relationship between shading patterns, module mismatch, bypass-diode operation, and multiple power-peak formation. Therefore, a systematic investigation considering diverse shading patterns and combined irradiance and temperature variations is required.

The study will quantitatively analyze parameters such as V_{GMPP} , I_{GMPP} , P_{GMPP} , **LMPP locations, peak magnitude, and peak separation**. Such characterization will provide a comprehensive understanding of the dynamic behavior of PV arrays under complex operating conditions. The outcomes will establish a scientific and experimental basis for developing a robust **global maximum power point tracking (GMPPT)** technique capable of reliably identifying and tracking the GMPP under partial shading conditions.

2. LITERATURE SURVEY

2.1 Overview

Photovoltaic (PV) systems exhibit nonlinear electrical characteristics that are strongly influenced by solar irradiance and cell temperature. Under uniform irradiance, a PV module or array generally exhibits a single maximum power point (MPP) on its power–voltage (P–V) characteristic. However, practical PV installations are frequently subjected to non-uniform irradiance caused by clouds, trees, buildings, dust, soiling, neighboring structures, and other environmental factors. Such non-uniform illumination produces **partial shading conditions (PSCs)**, resulting in electrical mismatch among interconnected PV modules.

The impact of PSC is particularly significant in series-connected PV arrays because the current of a series string is constrained by the module receiving the lowest effective irradiance. Bypass diodes are commonly incorporated to protect shaded modules from excessive reverse bias and hot-spot formation. However, their activation modifies the electrical characteristics of the array and can introduce multiple steps in the I–V characteristic and multiple peaks in the P–V characteristic. Consequently, the array may exhibit several **local maximum power points (LMPPs)** and only one **global maximum power point (GMPP)**.

Therefore, understanding the electrical behavior of PV arrays under different shading patterns is a fundamental prerequisite for developing reliable global maximum power point tracking (GMPPT) techniques.

2.2 Effect of Irradiance and Temperature on PV Characteristics

The electrical output of a PV cell is primarily dependent on solar irradiance and temperature. Variations in irradiance predominantly affect the photocurrent generated by the PV cell, whereas temperature has a stronger influence on the voltage characteristics. Reviews of PV maximum-power extraction methods identify irradiance and temperature as major environmental parameters responsible for changes in PV nonlinear characteristics.

Under uniform irradiance, the P–V curve generally contains a single dominant maximum. As irradiance changes, the short-circuit current and maximum power change substantially, while variations in temperature significantly influence the open-circuit voltage and the voltage corresponding to the MPP. Thus, an MPPT system operating under real environmental conditions must accommodate simultaneous changes in both irradiance and temperature. For the proposed research objective, this establishes the need to investigate PV-array characteristics not only under different shading percentages but also under **combined irradiance and temperature variations**.

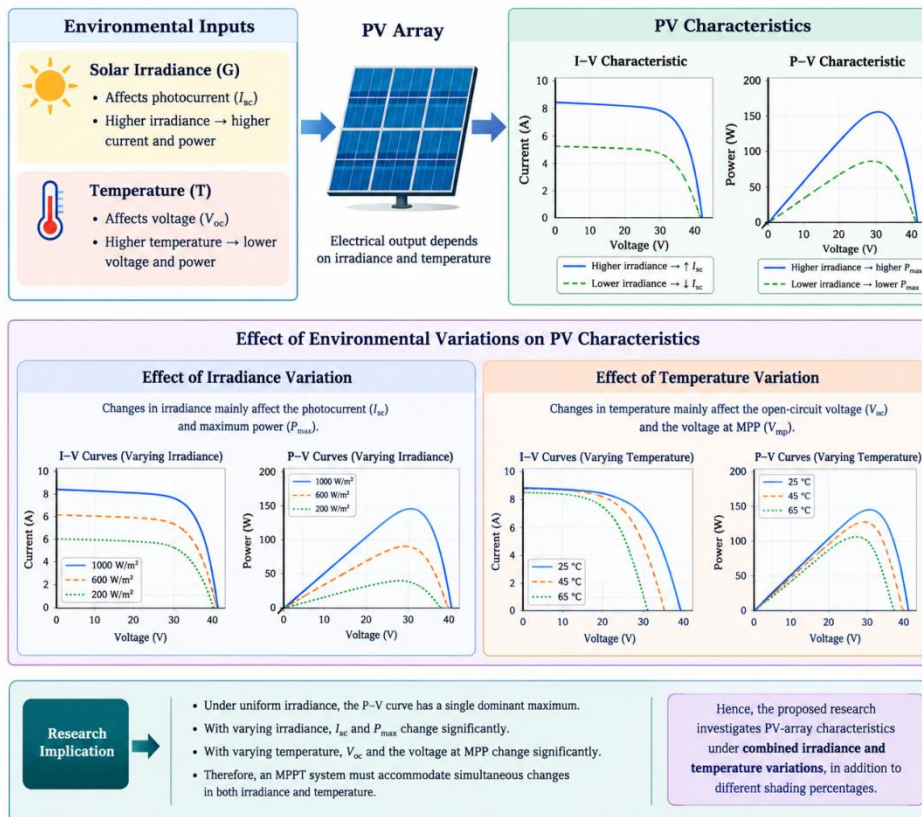


Figure-2.1: Effect of Solar Irradiance and Temperature Variations on the Electrical Characteristics of a Photovoltaic (PV) Array

2.3 Partial-Shading Conditions in PV Arrays

Partial shading occurs when different modules or cells within a PV array receive different levels of irradiance. Typical causes include: passing clouds, trees and vegetation, buildings and nearby structures, dust and soiling, shadows from poles and other installations, non-uniform module orientation, ageing and mismatch between modules.

The severity of PSC depends on both the **degree of irradiance reduction** and the **spatial distribution of shading across the array**. A comprehensive review by Belhachat and Larbes reported that PSC substantially reduces PV-array output and that different array configurations exhibit different responses to shading. Their review also highlights the importance of array topology and shading distribution in determining PV-array performance.

Similarly, recent reviews classify PV-array reconfiguration approaches according to different shading patterns and emphasize that PSC can produce significant mismatch losses and multiple peaks in the P-V characteristic. Thus, **the shading pattern itself becomes an important research variable**, rather than considering partial shading simply as a single operating condition.

2.4 Influence of Shading Patterns on I-V Characteristics

The I-V characteristic of a PV array under PSC differs significantly from that under uniform irradiance. When modules connected in series receive different irradiance levels, the current contribution of individual modules becomes unequal.

The activation of bypass diodes provides an alternative current path around shaded modules. While this prevents severe reverse-bias stress and reduces the likelihood of hot-spot damage, it also modifies the effective voltage contribution of the affected modules. Consequently, the I–V characteristic can exhibit multiple transition regions associated with different groups of shaded modules.

Ahmad et al. developed an analytical approach for investigating the effect of PSC on PV-array characteristics. Their analysis demonstrated that multiple local maxima are associated with the activation of bypass diodes and established relationships between the number of local maxima and the configuration of series-connected modules.

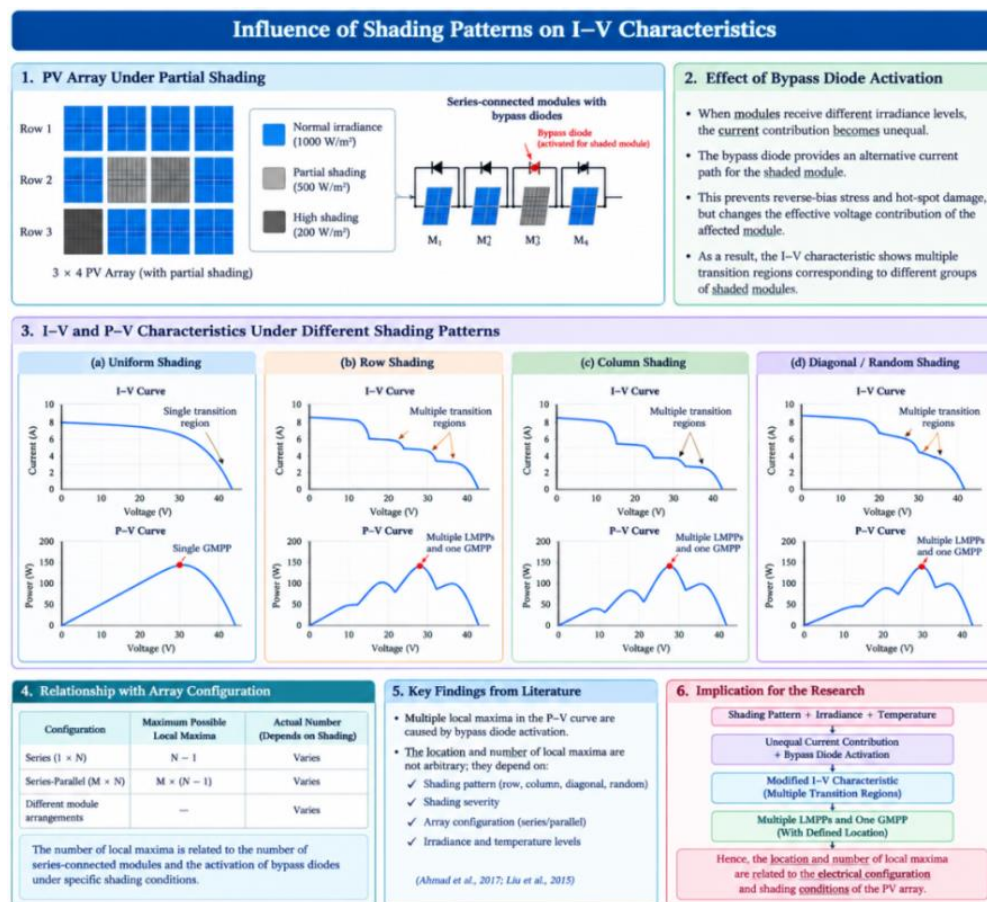


Figure-2.2: Influence of Different Partial Shading Patterns and Bypass Diode Activation on the I–V and P–V Characteristics of PV Arrays

This work is particularly relevant to our Objective because it demonstrates that the **location and number of local maxima are not arbitrary**; they are related to the electrical configuration and shading conditions of the PV array.

2.5 Formation of Multiple Peaks in P–V Characteristics

Under uniform irradiance, the PV-array P–V characteristic normally possesses one principal maximum. Under PSC, however, the curve may develop several peaks. These peaks correspond to different operating regions created by the mismatch among modules and the operation of bypass diodes.

Liu et al. reviewed GMPPT techniques for partially shaded PV systems and established that PSC produces a P–V characteristic containing a **global maximum power point and multiple local maximum power points**. This multi-peak

behavior makes conventional MPP tracking considerably more difficult because an algorithm may converge to a local rather than the global maximum.

Kandemir et al. similarly reported that non-uniform irradiance causes multiple maxima on the P–V curve and identified the difficulty of estimating the true global MPP among multiple candidate points.

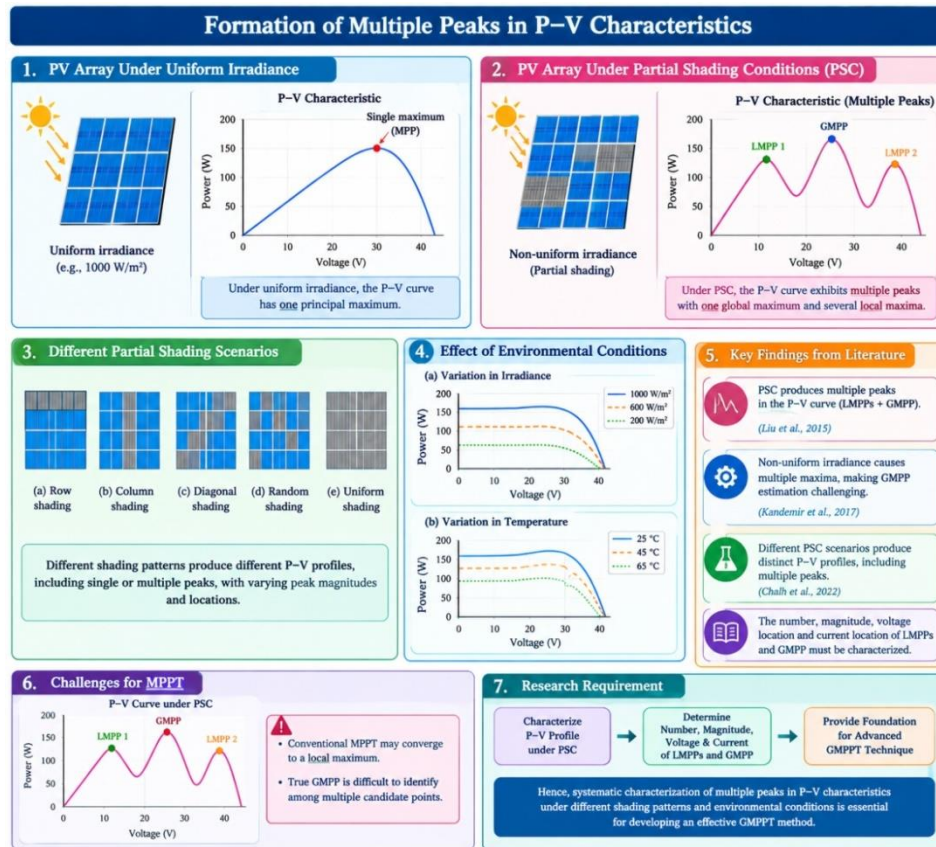


Figure-2.3: Formation and Localization of Multiple Local Maximum Power Points (LMPPs) and Global Maximum Power Point (GMPP) under Partial Shading Conditions

Experimental investigation by Chalh et al. further demonstrated that different partial-shading scenarios can produce different P–V profiles, including cases with multiple peaks. Their study specifically examined different PSC scenarios to characterize PV-array behavior and subsequently develop a GMPP controller.

Therefore, characterization of the **number, magnitude, voltage location, and current location of LMPPs and GMPP** is an important research requirement.

2.6 Localization of LMPP and GMPP

The localization of the GMPP under PSC is more complicated than conventional MPP tracking because the highest power point must be distinguished from several local peaks.

Ahmad et al. provided important analytical observations regarding the number and location of local maxima. Their study indicated that the maximum possible number of local maxima is related to the number of series-connected modules, while the actual number depends on the activation of bypass diodes under the particular shading condition.

This finding is significant because it indicates that **shading pattern** → **bypass-diode activation** → **I–V characteristic** → **P–V multi-peak structure** represents a causal chain that should be explicitly investigated.

Table-2.1: Parameters Considered for Comprehensive Characterization of LMPP and GMPP under Diverse Partial Shading Conditions:

Parameter	Investigation
Number of LMPPs	Number of local peaks generated
GMPP location	V_{GMPP} , I_{GMPP}
GMPP power	P_{GMPP}
LMPP locations	V_{LMPP} , I_{LMPP} , P_{LMPP}
Peak separation	Voltage/power distance between peaks
Shading severity	Percentage reduction in irradiance
Shading pattern	Uniform, diagonal, row, column, random, etc.
Temperature	Effect on voltage and power
Mismatch loss	Difference between ideal and shaded-array output
Bypass-diode status	Relationship with peak formation

This type of quantitative characterization would provide a stronger scientific foundation for the subsequent development of the proposed GWO-based MPPT technique.

2.7 Effect of Different Shading Patterns

The literature demonstrates that **the same shading intensity does not necessarily produce the same electrical response**. The spatial arrangement of shaded modules can substantially influence the P–V and I–V curves. PV-array studies have considered configurations and patterns such as: uniform shading, row shading, column shading, diagonal shading, random shading, short-and-narrow shading, short-and-wide shading, long-and-narrow shading, long-and-wide shading.

Research comparing PV-array topologies under these conditions has evaluated parameters including open-circuit voltage, short-circuit current, GMPP, LMPPs, mismatch losses, fill factor and efficiency. More recent reviews have similarly emphasized the importance of evaluating PV configurations under diverse shading patterns because the resulting mismatch losses and P–V characteristics can vary considerably. This supports the need for your research to use multiple representative shading patterns rather than a single predefined PSC scenario.

2.8 Analytical and Modeling Approaches

Several approaches have been reported for studying PV-array behavior under PSC:

a. Mathematical PV modeling

Mathematical equivalent-circuit models are used to obtain the I–V and P–V characteristics of PV modules and arrays under different irradiance and temperature conditions.

b. Simulation-based analysis

MATLAB/Simulink and other simulation environments are frequently used to construct PV arrays and impose different irradiance distributions. These approaches facilitate systematic investigation of shading patterns that are difficult to reproduce experimentally.

c. Analytical characterization

Ahmad et al. proposed an analytical approach to characterize the effects of PSC and formulated hypotheses regarding the number of local maxima. Such analytical treatment provides theoretical insight beyond simulation-only investigations.

d. Experimental characterization

Experimental investigations are valuable for validating simulated I–V and P–V characteristics. Chalh et al., for example, investigated different PSC scenarios experimentally and analyzed the resulting P–V characteristics.

Table-2.2: Comparative Literature Analysis

Author/Year	Major Focus	PSC Characteristics Investigated	Major Contribution	Research Limitation/Opportunity
Ramaprabha & Mathur (2012)	PV-array configurations under PSC	Array output and shading effects	Investigated shading effects on different PV configurations and bypass-diode-based mitigation	Greater emphasis can be placed on systematic LMPP/GMPP localization
Liu et al. (2015)	GMPP under PSC	Multiple peaks in P–V curves	Comprehensive classification of GMPP approaches	Focus is primarily GMPP rather than detailed electrical characterization
Kandemir et al. (2017)	Maximum power extraction	Irradiance, temperature and PSC	Reviewed nonlinear PV behavior and maximum-power extraction approaches	Further quantitative characterization of individual shading patterns is required
Ahmad et al. (2017)	Analytical PSC analysis	I–V/P–V characteristics	Established analytical relationships concerning local maxima	Scope can be extended to broader environmental and experimental conditions
Belhachat & Larbes (2021)	PV-array reconfiguration	Different shading configurations	Comprehensive review of reconfiguration methods	Reconfiguration is emphasized rather than detailed peak localization
Chalh et al. (2022)	Experimental PSC scenarios	Different shading conditions	Investigated P–V characteristics and GMPP under PSC	Further systematic analysis of combined irradiance temperature effects remains relevant
Recent reviews (2023–2026)	Advanced MPPT/reconfiguration	Multiple peaks and mismatch losses	Consolidated recent PSC mitigation approaches	Need for robust characterization supporting intelligent GMPP development

2.9 Critical Research Gap

Based on the reviewed literature, the following research gaps can be identified.

Gap 1: Limited unified characterization.

Many studies investigate specific shading patterns independently. A systematic framework that simultaneously considers **shading severity, spatial pattern, irradiance variation, temperature variation, and array configuration** can provide a more comprehensive characterization.

Gap 2: Insufficient emphasis on peak localization.

Existing studies establish the occurrence of LMPPs and GMPP, but there is scope for a systematic analysis of their: voltage locations, current locations, power levels, number of peaks, separation between peaks and movement under changing environmental conditions.

Gap 3: Interaction between irradiance and temperature.

Much of the PSC literature emphasizes irradiance mismatch. However, practical PV systems simultaneously experience changes in irradiance and temperature. A systematic study of their combined influence on **GMPP/LMPP formation and displacement** can strengthen the research foundation.

Gap 4: Need for a standardized PSC test matrix.

A structured test matrix involving different shading patterns and irradiance levels would facilitate reproducible evaluation and provide appropriate benchmark conditions for subsequent MPPT development.

Gap 5: Characterization-to-MPPT linkage.

The electrical characteristics identified in Objective should directly inform the design of the advanced GMPPT method in the next Objective. Therefore, the relationship between **shading pattern, electrical characteristics, peak formation, and GMPP location** should be explicitly established.

3. PROPOSED METHOD

The proposed methodology aims to systematically characterize the electrical behavior of photovoltaic (PV) arrays under diverse partial shading conditions (PSC) and varying environmental parameters. Initially, an appropriate PV cell/module model will be developed and validated using standard electrical parameters and manufacturer data. A series-parallel PV array configuration with bypass diodes will then be modeled to represent practical operating conditions. A comprehensive set of partial shading scenarios, including uniform, row, column, diagonal, random, and clustered shading patterns, will be considered with different shading intensities and spatial distributions. The irradiance and temperature parameters will be varied independently and in combination to investigate their influence on PV array characteristics. For each operating condition, the corresponding I–V and P–V characteristics will be generated and analyzed to identify the number, magnitude, voltage, current, and power associated with the LMPPs and GMPP. The influence of bypass diode activation and electrical mismatch among PV modules on the formation and displacement of multiple power peaks will also be investigated. A systematic PSC characterization matrix will be developed to establish the relationship between shading pattern, shading severity, environmental conditions, array configuration, and LMPP/GMPP characteristics. Quantitative parameters such as (V_{LMPP}), (I_{LMPP}), (P_{LMPP}), (V_{GMPP}), (I_{GMPP}), and (P_{GMPP}) will be extracted for comparative analysis. The resulting dataset and characterization framework will be used to identify critical operating conditions that

make GMPP localization challenging and will provide the necessary knowledge base for the development of the proposed GWO-based GMPPT technique in next Objective.

CONCLUSION

The investigation establishes that partial shading significantly alters the electrical behavior and power-generation characteristics of photovoltaic arrays. The analysis of I–V and P–V characteristics under diverse shading patterns, irradiance levels, and temperature conditions demonstrates the formation of multiple LMPPs and a distinct GMPP. The location and magnitude of these operating points are strongly influenced by shading severity, spatial distribution, module mismatch, array configuration, and bypass diode activation.

The study provides a systematic characterization of the relationship between partial shading patterns and the resulting multi-peak P–V characteristics. The quantitative identification of LMPP and GMPP parameters provides a reliable basis for understanding the complexity of GMPP localization under dynamic operating conditions. The findings highlight the limitations of conventional single-peak MPPT techniques when applied to PSC. Overall, the outcomes of Objective establish a comprehensive knowledge base for the development of an intelligent and robust GMPPT technique capable of accurately identifying and tracking the global maximum power point under complex and rapidly varying environmental conditions.

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