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Review article

Advancements in flexible power point tracking and power control strategies for photovoltaic power plants: A comprehensive review

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ABSTRACT

A tremendous growth in installed photovoltaic (PV) capacity and widespread use makes solar energy an important renewable energy source today. Voltage fluctuations and power quality problems are becoming more and more of a problem as the integration of PV power plants expands. In response, grid-connected PV systems' operational issues and the fluctuation of PV power generation have been addressed via the development of flexible power point tracking (FPPT) solutions. This review study provides a comprehensive analysis of FPPT strategies for PV power generation systems. It categorizes and describes various FPPT methods, studying their tracking performance under different working conditions and analyzing their underlying principles. One key advantage of FPPT strategies lies in their ability to operate PV systems below their maximum power point, thereby allowing for better control and active power reserve. Additionally, these strategies can provide essential grid support services, such as voltage control and frequency support. The work provides a baseline for scientists and researchers looking to adopt appropriate FPPT approaches. This research reveals common trends and efficient procedures for future investigations by contrasting methods based on their properties, such as their operating region selection and performance under partial shading circumstances.

1. Introduction

In recent years, solar energy has risen to the top among renewable energy sources, grabbing the attention of people all over the world. Due to its abundant and pure availability, solar power is extensively deployed for large-scale utilization. With advancements in technology, particularly in the form of cost reductions and improved efficiency of solar photovoltaic (PV) systems, solar energy has become more reliable and accessible than ever before. This has prompted a significant surge in its deployment worldwide, leading to a remarkable increase in installed PV capacity. In a span of just five years, from 2017 to 2022, the cumulative installed capacity of solar energy skyrocketed from 98 gigawatts (GW) (Tafti et al., 2020) to a staggering 1185 GW (Feldman et al., 2023), exemplifying its remarkable growth trajectory and positioning it as a key player in the global energy landscape.

Solar Photovoltaic (PV) systems are a vital source of clean energy. However, their output power isn't constant. It varies based on factors like sunlight intensity and temperature. To maximize power generation, PV systems rely on Maximum Power Point Tracking (MPPT) algorithms (Shams et al., 2021a; Pervez et al., 2021; Fares et al., 2021; Shams et al., 2021b; Deboucha et al., 2021; Ahmed and Salam, 2018; Ahmed et al., 2022). These algorithms ensure the system operates at the point on the I-V (current-voltage) curve where it produces the most power, known as the Maximum Power Point (MPP).

One of the most widely used MPPT techniques is Perturb and Observe (P&O) (Kermadi et al., 2020; Abouadane et al., 2020; Swaminathan et al., 2022; Bhattacharyya et al., 2021). It stands out for its simplicity, making it a popular choice for many systems. P&O works by

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periodically making small adjustments (perturbations) to the operating voltage of the PV system. It then observes the change in power output caused by this voltage change. If the power output increases with the voltage adjustment, the algorithm continues to perturb in the same direction, moving closer to the MPP. However, once the power output starts to decrease with further voltage adjustments, the algorithm reverses direction, ensuring it tracks the MPP continuously. While P&O is easy to implement, it has limitations. The constant adjustments cause the system to oscillate around the MPP, leading to some power loss. Additionally, P&O can be slow to react to rapid changes in sunlight intensity. For applications demanding higher efficiency and faster response times, Incremental Conductance (IC) (Shang et al., 2020; Motahhir et al., 2018; Kumar et al., 2018; Al-Dhaifallah et al., 2018; Necaibia et al., 2019) offers a valuable alternative. IC boasts faster response and better efficiency compared to P&O. It achieves this by directly comparing the instantaneous conductance (dI/dV) of the PV system with its operating voltage (V). At the MPP, a specific relationship exists between these values. IC exploits this by adjusting the operating voltage based on this comparison. If the measured conductance deviates from the expected value at the MPP, the algorithm adjusts the voltage to bring it closer. While IC offers significant advantages, it requires more complex calculations compared to P&O, increasing implementation complexity. Other techniques like Fractional Open-Circuit Voltage (FOCV) (Hsu et al., 2019; Baimel et al., 2019; Nadeem et al., 2020; Hassan et al., 2023) and Model Predictive Control (MPC) (Zhao et al., 2021; Irmak and Güler, 2020; Pradhan and Panda, 2020, 2022) offer accuracy by estimating optimal voltage and using mathematical models to optimize power output. However, their accuracy relies heavily on the chosen fraction values. These values can be less effective under rapidly changing operating conditions, limiting their suitability in certain scenarios.

The realm of MPPT techniques extends beyond these traditional methods. In recent years, advanced approaches like Fuzzy Logic Control (FLC) and Artificial Neural Networks (ANN) (Rezk et al., 2019; Aly and Rezk, 2020; Dehghani et al., 2021; Bag et al., 2018; IEEE Staff, 2013; Padmanaban et al., 2019; Priyadarshi et al., 2020; Ibrahim et al., 2021) are gaining traction. FLC utilizes fuzzy logic rules to make decisions about adjusting the operating voltage based on measured voltage and current. ANNs, on the other hand, are trained on data sets to learn the relationship between operating conditions and the location of the MPP. These techniques offer significant advantages, including high efficiency and faster response times, especially under challenging conditions like partial shading where traditional methods struggle. However, implementing FLC and ANN requires more complex programming and computational resources, which may not be feasible for all applications. As the need for efficient solar energy production grows, the development of MPPT techniques continues to evolve. Metaheuristic optimization methods, like the cuckoo search algorithm (Mosaad et al., 2019; Hussaian Basha et al., 2020) and particle swarm optimization (PSO) (Belghith et al., 2016; Chtita et al., 2022; Javed and Ishaque, 2022), explore search spaces to converge on the MPP. By combining the strengths of different approaches, hybrid techniques are emerging. These methods leverage the advantages of simpler methods like P&O for initial tracking, followed by a more precise technique like IC for fine-tuning around the MPP. Selecting the most suitable MPPT technique for a specific application requires careful consideration of factors like system complexity, cost, efficiency demands, and environmental conditions. Understanding the strengths and weaknesses of various techniques like P&O, IC, FOCV, FSCC, soft computing methods, and hybrid approaches empowers engineers to make informed decisions, maximizing the energy harvest from solar PV systems. Global MPPT methods (Liu et al., 2014; Eltamaly and Farh, 2019; Kalogerakis et al., 2020; Lu et al., 2022; Ahmed et al., 2023a) optimize multi-panel or multi-inverter setups by coordinating power extraction and control strategies. Decreasing PV panel costs makes advanced MPPT methods more viable, maximizing efficiency and energy output. These advancements accelerate PV adoption as a sustainable power source.

Nomenclature

Acronym			
AAPC	Absolute Active Power Control	PSO	Particle Swarm Optimization
BESS	Battery Energy Storage System	PV	Photovoltaic
BNS	Binary Nonlinear Search	PVPPs	Photovoltaic Power Plants
CPC	Constant Power Control	PWC	Power Weakening Control
CPG	Constant Power Generation	RGT	Reserve Generation Technique
CPP	Constant Power Point	RPPT	Reserve Power Point Tracking
CPP-L	Constant Power Point at the left side of MPP	SCC	Short-Circuit Control
dcMG	dc Microgrid	SoC	State of Charge
DPC	Delta Power Control	SSJ	Search-Skip-Jump
DPV	Distributed Photovoltaic	TVI	Target Voltage Iterations
FOCV	Fractional Open Circuit Voltage		
FPPT	Flexible Power Point Tracking	*Latin Symbols*	
GCPVPPs	Grid-Connected Photovoltaic Power Plants	D_{main}	Main Duty Cycle
GFPPT	Global Flexible Power Point Tracking	D_{ripple}	Perturbation signal
GMPPT	Global Maximum Power Point Tracking	D_{scan}	Duty Cycle for Scanning
GW	GigaWatts	e_{min}	Minimum Error
HC	Hill-Climbing	g_{mpp}	Global Maximum Power Point
INC	Incremental Conductance	h_k	Upper Limit
LCOE	Levelized Cost of Energy	Irr	Irradiance
LMPP	Local Maximum Power Point	l_k	Lower Limit
MCLC	Minimum Current Limiting Control	p_{fpp}	Power At Flexible Power Point
MPC	Model Predictive Control	p_k	Output Power
MPP	Maximum Power Point	p_{limit}	Constant Power Limit
MPPT	Maximum Power Point Tracking	p_{pv}	Output Power of Photovoltaic System
MPT	Maximum Point Trapezium	p_{ref}	Reference Power
NPC	Neutral Point Clamp	v_{fpp}	Voltage At Flexible Power Point
P&O	Perturb and Observe	v_k	Output Voltage
PI	Proportional Integral	v_{pref}	Voltage At Reference Power
PRC	Power Reserve Control	v_{pv}	Output Voltage of Photovoltaic System
PSC	Partial Shading Condition	v_{step}	Perturbation Step

While MPPT approaches are excellent at maximizing the output from solar PV panels, they largely concentrate on power output optimization without taking grid integration issues into account. Voltage oscillations, low system inertia, and problems with power quality become more prevalent as the use of PV power plants spreads (Li et al., 2020; Kumaresan et al., 2021a). Flexible power point tracking (FPPT) strategies have emerged as a crucial solution to address the challenges associated with the variability of PV power generation and the operational issues faced by grid-connected PV systems. The use of FPPT techniques offers a way to control the PV system's power output to a predetermined level, easing integration difficulties. By operating PV systems below their MPP with active power reserve, FPPT strategies enable better control over PV generation. This control mechanism allows for more stable and reliable power output from PV systems, reducing the risk of overloading, overvoltage, and other operational issues. One notable benefit of FPPT strategies is their ability to provide grid support services, such as voltage control and frequency support (Dehghanitafti et al., 2022; Dehghani Tafti et al., 2023; Zhong et al., 2020). A delta power constraint, for instance, can be implemented to store a portion of the PV panels' active power during grid frequency variations. This reserved power can be utilized to help stabilize the grid and support its operation during challenging conditions. In order to overcome the difficulties brought on by the fluctuation of PV power generation, FPPT solutions are necessary. This helps more people use solar panels while making them work smoothly with existing power grids.

There are two main categories for FPPT algorithms. The first strategy entails changing the power conversion stage's control mechanisms in a PV system, either by adjusting the controller of the DC-DC converter in two-stage systems (Utrilla et al., 2023) or the DC-AC inverter controller in single-stage grid-connected PV power plants (GCPVPPs). These adjustments control the power output of the PV system and align it with the desired power reference using proportional-integral (PI) controllers or other control techniques. Various methods fall under this category, such as those discussed in the papers (Tang et al., 2015; Yang et al., 2014a; Mirhosseini et al., 2015). The second strategy is to modify the voltage reference of PV strings in accordance with the necessary power reference, taking into account the power-voltage (P-V) characteristics of the PV panels. These algorithms allow quick dynamics and consistent power generation from GCPVPPs by dynamically altering the operation point of the PV strings without altering the converter controllers. Some methods falling under this category are discussed in papers (Tafti et al., 2018; Sangwongwanich et al., 2016, 2018, 2017a; Tafti et al., 2016). The FPPT algorithms provide effective strategies for regulating the power output of PV systems by either modifying the converter controllers or adjusting the voltage reference of PV strings, enabling efficient power generation in various operating conditions.

In recent years, many FPPT algorithms have been proposed, and most of them are incorporated into the literature. To increase the effectiveness of the system, some works updated the previously used methodology, and others developed new algorithms that solved issues with the FPPT's tracking speed and accuracy. In this review work, we have discussed and compared 33 FPPT methods and have done a detailed discussion of different FPPT methods by dividing them into different categories. Some of the proposed works can work effectively well under fast-changing irradiance (Bi et al., 2023a) without making the system much more complex and cost-ineffective. This analysis can uncover patterns in research and suggest effective methods for future studies. It can also summarize findings from different papers, showing where researchers agree or disagree. This helps readers understand the topic thoroughly and see where more research is needed.

This review delves into 33 different research papers focusing on FPPT and Constant Power Generation (CPG) methods. Unlike many other reviews that mainly focus on the performance of FPPT techniques, this study takes a unique approach. Instead of just looking at how well these methods perform, it categorizes them based on their operational regions and how well they work under Partial Shading Conditions (PSC) and different weather conditions. While some previous works briefly touched on these aspects, their main focus was usually on explaining the performance of different FPPT methods and the specific methods they use. For example, one notable research paper (Tafti et al., 2020) categorized FPPT methods based on how they track reference power. However, our approach is different because we categorize them based on their operational regions and how they perform under different environmental conditions. Additionally, many previous works only included a limited number of research papers, giving a narrower view of FPPT and CPG methods. In contrast, this research includes a wider range of state-of-the-art literature, totaling 33 relevant papers. This comprehensive approach ensures a more thorough analysis and a better representation of the latest advancements in the field. By categorizing FPPT and CPG methods based on their operational characteristics and adaptability to challenging environmental conditions, this work fills an important gap in the existing literature, offering valuable insights for both researchers and practitioners.

The remaining part of the document is structured as follows: First, in Section 2, we present an overview of various FPPT algorithms that have been proposed in the literature, focusing on their specific roles within the solar PV system and their ability to enhance its overall efficiency by targeting specific areas. Then, in Section 3, we engage in a comprehensive discussion and comparison of the different FPPT techniques. Moving on to Section 4, recommendations have been made for the best-performing methods. In Section 5, the conclusion of the review paper is presented. Finally, Section 6 presents the future works by highlighting the future potential and opportunities for further research in the field of FPPT strategies.

2. Literature review of FPPT AND CPG methods

The literature has introduced a number of FPPT strategies, each of which has unique benefits for tracking response and minimizing error. These techniques exhibit preferences for operating on different sides of the MPP. Some demonstrate superior performance on the right side of the MPP (Tang et al., 2015; Yang et al., 2014a; Sangwongwanich et al., 2018; Batzelis et al., 2018; Tafti et al., 2019a; Yang et al., 2014b; IEEE Industry Applications Society., 2013), while others excel on the left (Sangwongwanich et al., 2016; Bi et al., 2023a; Zhu et al., 2021; Ahmed et al., 2023b). Additionally, certain methods exhibit versatility by performing effectively on either side (Dehghanitafti et al., 2022; Tafti et al., 2016, 2019b; Yan et al., 2023; Tafti et al., 2017; Sangwongwanich et al., 2017b; Yang et al., 2017; Lei et al., 2023) of the MPP. There are benefits and drawbacks to operating two-stage grid-connected PV systems on either side of the MPP. While the right region operation gives lesser current and, as a result, fewer ohmic losses, the left region operation greatly lowers power oscillations. The specific application requirements determine the operating region to be used. Most FPPT techniques demonstrate resilience under PSC (Mahmoodi Tabar et al., 2023; Zhu et al., 2022) allowing them to maintain accurate tracking despite non-uniform irradiance. However, there are FPPT methods specifically designed to address sudden changes in irradiance and temperature, making them less suitable for scenarios primarily focused on tackling PSC challenges. Considering these criteria, FPPT methods can be categorized and chosen based on their specific strengths and applicability.

2.1. Classification based on the operating region

FPPT techniques can be categorized based on their preferred region of operation concerning the MPP. Some techniques excel in tracking the MPP on the right side, while others exhibit superior performance on the left side of the MPP. These region-specific FPPT techniques are designed to maximize power under particular circumstances. The techniques designed for the right side of the MPP focus on capturing the optimal power output in high irradiance situations, where the operating voltage is higher. On the other hand, FPPT techniques specialized for the left side of the MPP aim to maximize power extraction in low irradiance scenarios, where the operating voltage is lower. Additionally, there are FPPT methods that exhibit versatility and can effectively track the MPP on either side. The selection of an appropriate FPPT technique based on the desired region of operation plays a vital role in optimizing the power output of photovoltaic systems. The structure of the literature works has been illustrated by a figure shown in Fig. 1.

2.1.1. Left side operation

The nonlinear hybrid control system presented in the paper (Zhu et al., 2021) is intended to produce quick convergence and minimal power oscillations in a steady state for PV systems. Fig. 2 shows an illustration of the high-performance constant power generation (CPG) operation. To avoid instability, the control system places the operating point to the left of the MPP. A single combination of voltage and current is used to estimate the total available power speeds convergence under a variety of environmental conditions. The control system is affordable since it can be added to PV systems that are already in place without the need for additional hardware. The control system runs in two modes, MPPT and CPG which transition seamlessly to provide dependable performance under a variety of circumstances. The control system's benefits are demonstrated by comparative analyses with cutting-edge CPG techniques in a variety of circumstances. The efficiency of the control mechanism has been further supported by experimental

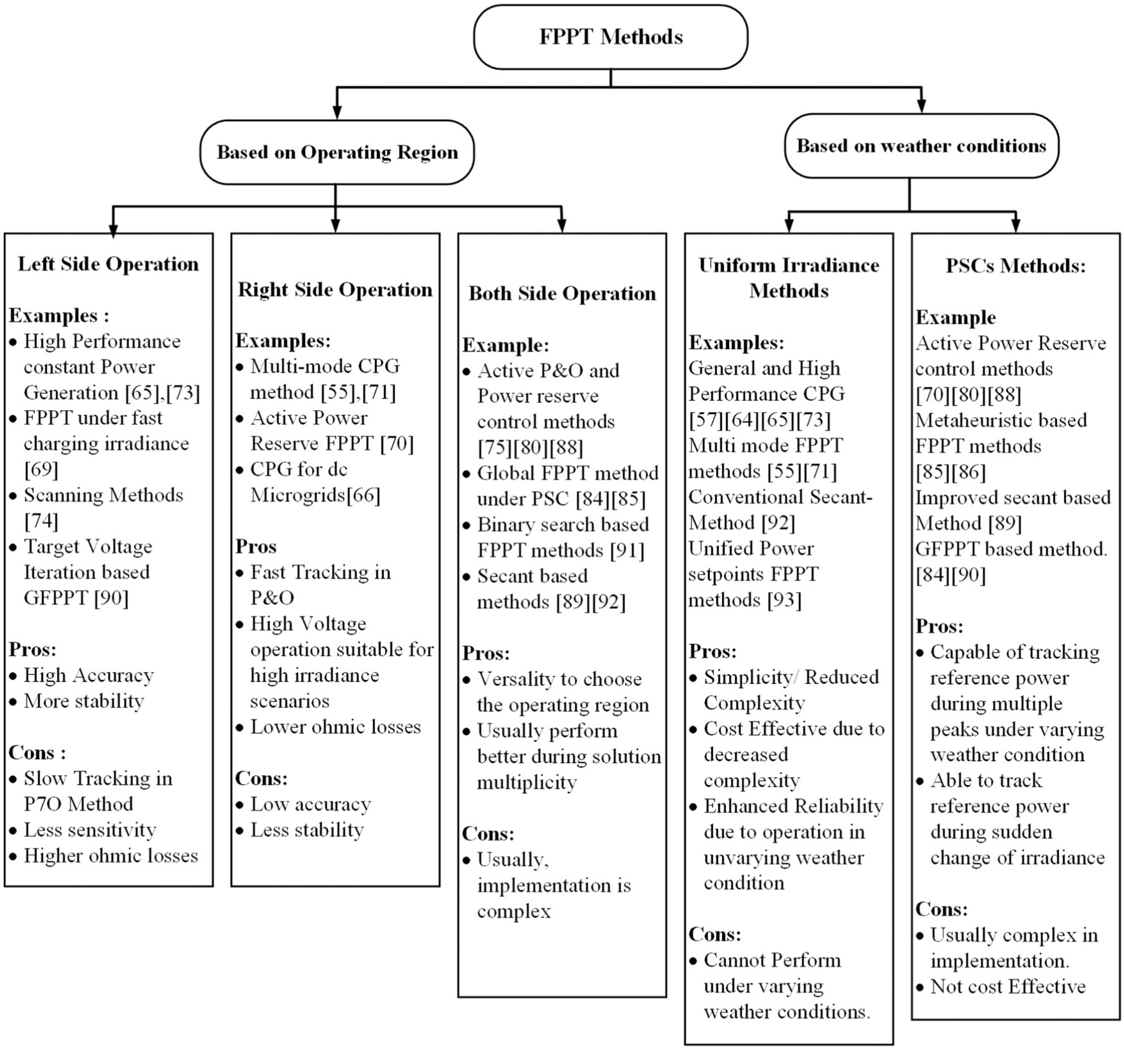

Fig. 1. Overview and classification of the PV FPPT and CPG methods present in the literature.

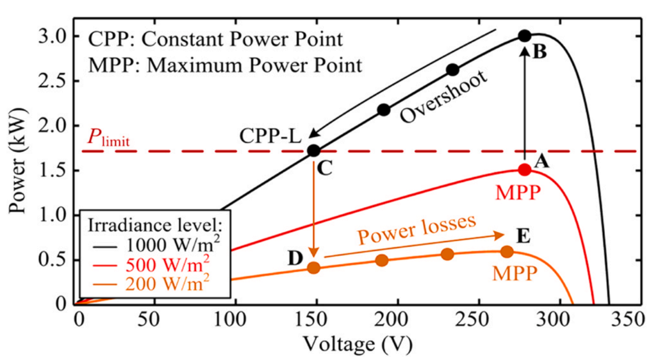

Fig. 2. Demonstration of the CPG during a fast-changing irradiance (Zhu et al., 2021).

validation.

The PV arrays' right side of the MPP is the sole area where the single-stage P&O-CPG algorithm may operate. In the event of a rapid irradiance fall, this results in control problems. In order to address this, a two-stage grid-connected PV system is proposed in (Sangwongwanich et al., 2016) to increase the P&O-CPG algorithm's operational range by controlling the PV output power at the MPP's left side. An efficacious CPG approach is recommended after the traditional P&O-CPG techniques are empirically confirmed, compared, and contrasted. The disadvantages of the various CPG methods employed for MPPT in PV systems are explored in (Bi et al., 2023a). Due to its great resilience, the P&O-based CPG is regarded as the best option. Modified CPG algorithms are suggested as a way to increase tracking accuracy in steady-state and fast-changing irradiance conditions. Additionally, CPG methods are presented based on nonlinear search and adaptive step size. The mentioned approach uses the enhanced FPPT algorithm, which combines an improved CPG approach with a modified MPPT strategy. By addressing the shortcomings of current CPG algorithms, this approach seeks to increase tracking precision and speed while minimizing complexity and battery consumption. The research work in (Ahmed et al., 2023b) proposed a novel FPPT approach that overcomes the drawbacks of current PSC operation techniques. In comparison to cutting-edge algorithms, the suggested method has various advantages, including fast-tracking capabilities. It may be used with any number of PSC patterns and operates on the left of the MPP to provide robustness. Faster tracking is made possible by the algorithm's elimination of the necessity for additional P-V curve scanning after locating the targeted power peak. To perform the FPPT operation, it uses both the traditional search-skip-jump (SSJ) technique and alternative approaches. The suggested algorithm's viability and improved performance in terms of operational criteria are shown through comprehensive simulation and experimental validation under diverse circumstances. The suggested method's advantages in terms of PSC operation, stability, accuracy, control complexity, and validation procedure are highlighted by comparison with previous FPPT algorithms.

2.1.2. Right side operation

The authors in (Batzelis et al., 2018) describe a two-stage PV inverter system where a P-Q control algorithm maintains a constant dc-link voltage and a DC-DC converter adjusts the operating point. Five subsystems make up a more complex control method that is presented. The MPPs estimator block continually calculates the maximum power using voltage and current data, while the reserves module sets the planned power and the control module controls the duty cycle to monitor the power reference. The sampling and ripple control module introduces a perturbation pulse to allow a regulated oscillation of the operating point. The scan block quickly does a curve scan to change the duty cycle when a shadow emerges. Depending on the operating mode, the final duty cycle will be either (*Dmain* + *Dripple*) or *Dscan*. The algorithms used in earlier research assume a brief period of grid voltage sag and no substantial climatic changes, which makes it challenging to extract consistent power from PV strings for extended periods. By including a traditional MPPT algorithm to raise PV power and a PI controller to lower PV power towards the target value, the multi-mode-based FPPT algorithm in (Tafti et al., 2019a) attempts to expand the application of these methods for continuous operation. This suggested approach may be used to transfer the operation point to the right or left sides of the MPP and can be used for single- and two-stage GCPVPPs. Fig. 3 shows a demonstration of how the multi-mode FPPT approach operates.

The paper (Tang et al., 2015) suggested a multi-mode operation boost converter for PV power systems. When there is a little voltage drop, the converter continues to operate in MPPT mode. The converter switches to constant power control (CPC) mode when the PV array reaches the three-phase inverter's maximum allowable power. The short-circuit current (SCC) mode is triggered and the smooth transition idea with the derived incremental duty cycle is employed to prevent circuit damage in the case of a significant grid fault. The research paper also proposes the maximum current limitation control (MCLC) strategy

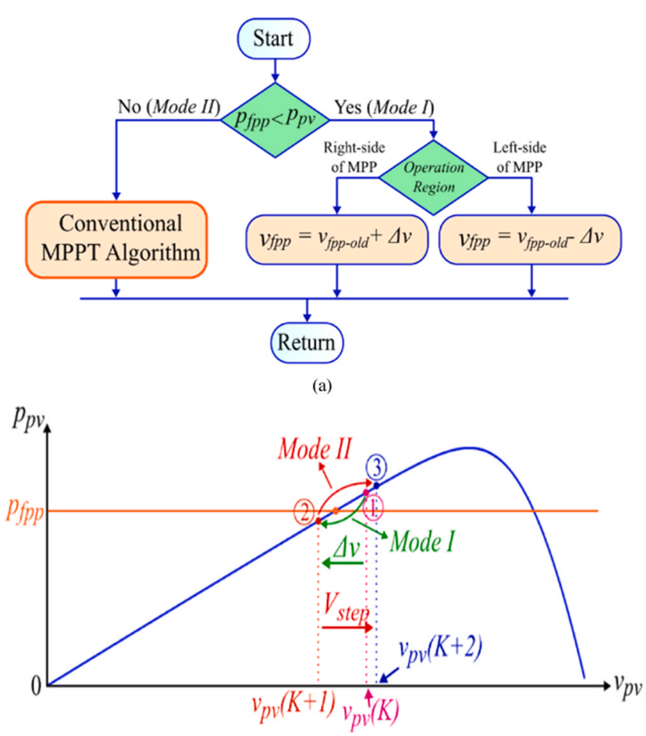

Fig. 3. a) The multi-mode algorithm's control diagram and b) An illustration of the multi-mode method (Tafti et al., 2019a).

for the three-phase inverter and provides mathematical derivations and experimental results of a 5 kVA prototype to validate the suggested control method. In some circumstances, such as when the grid frequency is too high or when the PV power exceeds the maximum power output of the electronic converter, solar PV power plants must be able to limit their power output. There are several MPPT algorithms available to control power output, however, they frequently overlook the requirement to work in both MPPT and FPPT (Aourir and Locment, 2020) modes. The innovative approach suggested in (IEEE Staff, 2013) maintains stability and prevents voltage dips in the PV voltage while enabling operation in both modes. Even in the face of abrupt fluctuations in irradiance, the approach maintains high dynamics for power response and guarantees stability in both MPPT and FPPT modes.

The distributed grid faces difficulties as a result of the growing use of PV systems, necessitating infrastructure modifications to keep things stable. To provide grid support for PV systems at a high penetration level, which requires flexible regulation of active power, grid codes are being updated. Energy storage and system capacity increase are solutions, but they come at a great price. Lowering the highest possible feed-in power of PV systems can reduce the load on the distribution grid. In the study in (Yang et al., 2014b), a CPG control approach for PV inverters is put forth as a solution to these problems. In the research in (Yang et al., 2014a), a hybrid power control approach for PV inverters is proposed. It combines an MPPT mode with a CPG control mode. When the DC power from PV panels hits a certain threshold, the CPG mode kicks in; when it falls below that threshold, the MPPT mode kicks in. The suggested idea can help with system-level power management by lowering the necessary power ratings and extending the lifespan of switching devices. The research addresses the control strategy's deployment, viability, and efficacy. The CPG control, also known as power curtailment, was attained in (Sangwongwanich et al., 2018) by altering the MPPT algorithm at the level of the PV inverter. In this method, the PV system runs in MPPT mode and injects the most power possible until the set-point Plimit is reached, at which time a constant active power of $P_{PV} = P_{limit}$ is injected. When surplus PV power cannot be used by the load or battery, the PV converter may experience over-voltage and reliability problems with the system. Resistor banks and wired communication are not workable alternatives. By shifting the operating point away from the maximum power point, the study in (IEEE Industry Applications Society., 2013) suggested a power weakening control (PWC) to limit or weaken excessive PV power. PWC is made possible by the addition of an additional DC-link voltage controller, which is automatically switched by a hysteresis controller to ensure stable operation by removing undesired surplus power.

2.1.3. Both side operation

By adding an oscillating operation point near the power reference, the adaptive algorithm for FPPT in (Tafti et al., 2019b) enhances the P&O approach. Between each voltage reference calculation, the algorithm adds a measurement step to measure the PV voltage and power. The controller adjusts the PV voltage to its reference value during the first half of the sample time, increasing the PV output power. The voltage reference does not vary, and the PV output power does not change from the beginning to the conclusion of the sample time. This strategy enables the computer to manage the PV output precisely even during sudden drops in solar irradiation. The working of the adaptive control scheme is illustrated in Fig. 4.

The paper (Dehghanitafti et al., 2022) suggested a method for controlling power reserve using FPPT to enhance grid frequency responsiveness in distributed PV (DPV) inverters. For quicker frequency recovery following a disruption, it also suggests a recovery operation mode. The efficacy of the algorithm is examined using a composite load model, and its dynamic performance is tested under frequency disturbances. To increase the battery lifespan by controlling the charging current, the paper suggests a centralized control method for standalone DC microgrids (dcMG) equipped with a PV system and a battery energy

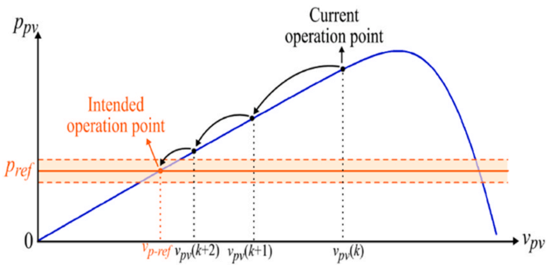

Fig. 4. Illustration of the working of the adaptive P&O FPPT technique (Tafti et al., 2019b).

storage system (BESS). The battery is utilized as a backup asset to regulate the voltage of the dcMG, and the PV system is employed as the primary aid to manage the dc-link voltage. Based on the instantaneous PV reserve power and the battery SoC information, a fuzzy logic control approach is employed to calculate the regulated charging current. The suggested method in (Yan et al., 2023) lessens the battery's stress when charging and draining to increase battery life. Multilevel converters are effective for converting high-power energy. For multi-string PV power plants (PVPPs), a single DC-link and 3 L-NPC inverter layout was suggested, enabling maximum power extraction from PV strings under partial shadowing. Previous research suggested methods for injecting active/reactive currents during voltage sags, but they didn't make use of the inverter's full current capability and could have broken grid code rules. To determine the dq-axis current references during voltage sags, this study in (Tafti et al., 2017) suggests a technique based on the inverter current limits, grid code specifications, and the quantity of harvested power from PV strings. To minimize the quantity of extracted power from PV strings to the amount of active power that can be injected into the grid, a coordinated MPPT algorithm is also included for the DC-DC converters.

Based on the P-V curve features, the research study in (Tafti et al., 2016) suggested an algorithm that determines the voltage needed for a PV panel to deliver a specific output power. The algorithm takes the role of the P&O MPPT technique during a voltage sag and determines the reference voltage based on the necessary reference power. Without further modification or controller, the reference voltage may then be sent into the DC-DC converter controller. The use of delta power control (DPC) in PV systems is covered in (Sangwongwanich et al., 2017b). In the suggested system, each PV string is separately controlled by a DC-DC converter utilizing a multi-string PV inverter topology. For the other PV strings to function in CPG mode, one master PV string calculates the available PV power and sets power limitations. This method is a less expensive way to deploy DPC since it doesn't call for energy storage systems or irradiance measurements. In (Yang et al., 2017), the author proposed absolute active power control (AAPC) as a solution to address overloading issues caused by peak power production of PV systems. AAPC limits the maximum feed-in power, requiring only modest software adjustments and offering affordability. The study finds that implementing AAPC does not significantly reduce energy yield, but it reduces thermal stresses on power devices, improving system reliability and extending the PV system's lifespan. The study offers a method for choosing the ideal power limitation level taking into account long-term mission characteristics and the effect on energy yield and system longevity to lower the levelized cost of energy (LCOE).

To offer frequency support in big power networks, the authors in (Lei et al., 2023) suggested using PVPPs with an FPPT algorithm. PVPPs may simulate inertia reaction during emergencies by setting aside power and applying droop management, providing a less expensive option to machineries like synchronous condensers and BESS. The coordination of damping control enhances frequency stability even further. Despite not being extensively used, inertia assistance from PVPPs without BESS has been tested in the field and modeling. Utilizing machine learning algorithms and phasor measuring units, real-time assessment of system inertia enables adaptive PV power reserve regulation, which optimizes reserve levels based on shifting inertia levels throughout the day. With this approach, research holes are filled and the usefulness of frequency response with PVPPs in massive power systems is illustrated.

2.2. *Classification based on the ability to perform under PSC*

FPPT techniques can also be categorized based on their ability to perform under PSC. Even in the presence of inconsistent irradiance brought on by PSC, the majority of FPPT approaches show durability and effectiveness in tracking the MPP. These methods were designed expressly to address the difficulties presented by partial shading by providing precise tracking of the reference power (P_{ref}) despite fluctuations in irradiance throughout the PV modules. These FPPT techniques dynamically modify the operating point of individual PV modules to minimize the effects of shade and maximize power production. They do this by utilizing sophisticated algorithms and control mechanisms.

2.2.1. *Methods that can be performed under PSC*

To provide constant power management and power ramp-rate control in PV systems under PSC, the authors in (Tafti et al., 2022) suggest the global FPPT (GFPPT) method. The GFPPT method with CPC and power reserve control (PRC) is shown in Figs. 5(a) and 5(b) respectively. The suggested approach does not include intelligence or optimization-based techniques and is adaptable to PV arrays with any number of power peaks. The effectiveness of the recommended algorithms in preserving CPG or PRC functions in PV systems under dynamically changing PSC patterns has been demonstrated through experimental tests. The advantage of the suggested method is that it can be used in constant power and PRC scenarios, which minimizes the complexity of the method implementation and provides computational superiority in comparison to alternative options in practical systems.

The authors in (Xie and Wu, 2022) used the hill climbing and PSC algorithms (HC&PSO) to offer a unique FPPT approach for PV systems under PSC. The recommended technique extracts the turning point data from the P-V characteristic curve and solves it with the HC algorithm to obtain the interval of the local maximum power point (LMPP). The FPPT algorithm's reference voltage is solved using the PSO algorithm, which also creates a new objective function. The HC&PSO-based FPPT algorithm prevents trapping into an LMPP under PSC and assures smooth system operation with reduced tracking error. To overcome the difficulties of running a PV system under PSC, which can lead to many peaks in the P-V curve, the paperwork (Kolakaluri et al., 2023) suggests a unique approach based on meta-heuristic optimization. The method

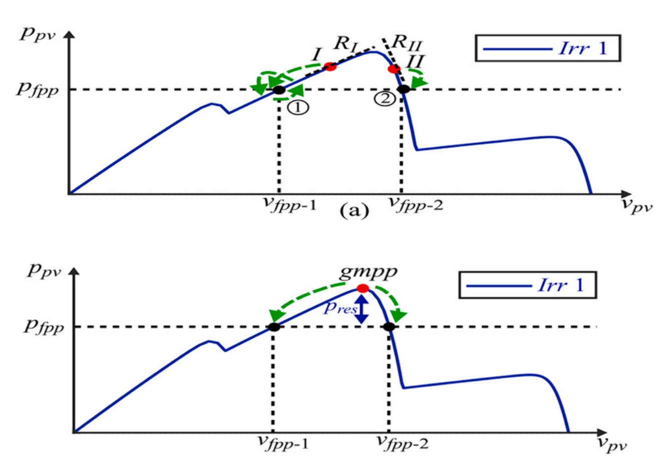

Fig. 5. Principles of working of GFPPT for a) with CPC and b) with PRC (Tafti et al., 2022).

effectively addresses the problems that FPPT control encounters with solution multiplicity and local peak blocking. It calculates the most energy-efficient operating point for the power reference line and maximizes power conversion efficiency by establishing the system equilibrium at the highest voltage possible while strictly following the power reference instructions. While performing meta-heuristic optimization, the duty ratio quantization problem is considered, and suitable logical techniques are developed to trace disturbances. To offer power reserve control and regulate produced power to its reference, the reserve power point tracking (RPPT) algorithm, which switches the operating point between two preset voltages on the PV curve, is recommended by the research work in (Narang et al., 2023). Under all operational situations, including PSC, RPPT can easily observe changes in the MPP and calculate the dispatchable reserve power that is available. In comparison to measurement-based methods, RPPT reduces volatility in the amount of power fed into the grid, can be implemented without requiring hardware changes, and is independent of PV panel models. The quick dynamic reaction of RPPT can also boost grid frequency and increase solar energy penetration.

To run a PV system at the appropriate power under PSC, the study in (Verma et al., 2021) suggested a straightforward technique called the reserve generation technique (RGT). The approach, which works for PV systems with two-peak P-V curves, is based on an MPPT algorithm with PSC. The method may be modified to accommodate multi-peak P-V curves and both left and right-peak shading patterns. Other PSC MPPT techniques, though, are documented in the literature. In the paper (Kumaresan et al., 2023), the author introduces an improved secant-based GFPPT algorithm, which can work on PSC in solar PV systems. It alters the traditional secant approach by maintaining one set point while changing the other, allowing convergence to the solution. An important problem with the previous FPPT algorithms is resolved by the proposed method, which can track the reference power on both the left and right sides of the GMPP. The proposed study in (Bi et al., 2023b) offered a GFPPT algorithm based on target-voltage iterations (TVI) as a remedy for the drawbacks of existing approaches like maximum power trapezium (MPT), search-skip-jump (SSJ), and MPT+SSJ-based GFPPT algorithms, particularly in the context of PSC. The TVI-based GFPPT algorithm was created with FPPT under PSC in mind. Compared to sophisticated FPPT algorithms, it offers computational simplicity and efficiency. The TVI-based system monitors the reference power by skipping rounds rather than utilizing lengthy searching procedures, leading to a quicker tracking speed and lower energy discrepancies. It addresses the drawbacks of the MPT, SSJ, and MPT+SSJ-based algorithms by providing a more effective and efficient technique for GFPPT under PSC conditions.

2.2.2. *Methods that are unable to be performed under PSC*

An FPPT methodology is described in the suggested technique used in (Gomez-Merchan et al., 2021) as a binary nonlinear searching (BNS) algorithm. Fig. 6 illustrates the BNS-based FPPT's operation. A data set is split into two subgroups using the BNS algorithm according to a goal value. First, dynamic restrictions are defined, and the desired value is compared to the datasets' median value. If the target value is in the upper subset and is below the middle value, it is updated; if it is in the lower subset and is above the middle value, it is not updated. Until the goal value or the value that is the closest is found, the process is repeated. The number of comparisons needed by the BNS algorithm is calculated using the dataset size, *N*. The BNS method is more efficient than a linear approach in terms of computational work, which reduces convergence time.

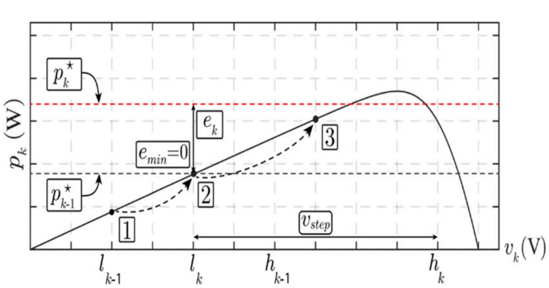

Fig. 6. The BNS FPPT Algorithm's method of operation. The operative points at instants *k-1*, *k*, and *k+1* are points 1, 2, and 3, respectively (Gomez-Merchan et al., 2021).

The suggested FPPT algorithm in (Kumaresan et al., 2021b) allows us to find the solar PV system's MPP and flexible power point (FPP). It utilizes a reference curve for maximum power output and operates on either side of the MPP depending on predetermined operating areas. The algorithm works on the principle of secant methodology, and the reference voltage V_{ref} is established at the point where the line linking two places and the power reference line intersects. The approach can be applied on both sides of the MPP since it provides for adjustable side-of-operation selection based on the application. Working on the right produces faster transitions but greater oscillations, whereas working on the left produces faster transitions but smaller ohmic losses. The FPPT algorithm is attractive for PV systems since it offers high MPP tracking accuracy and speed. An integrated approach for power curtailment in solar PV systems that incorporates a real-time curve-fitting-based MPPT and an improved P&O-based FPPT has been devised by the authors in (Paduani et al., 2022) The technique does away with the requirement for an external ripple by taking advantage of the P&O's oscillating characteristic to provide a useful measuring window for curve-fitting. It also offers quick frequency response for improved grid support without the need for PV cell temperature sensors or irradiance sensors. A fast-convergence method, a way to separate the effects of irradiance variations, and a fresh approach to controlling output power ripple are some of the algorithm's main contributions. The simulation findings and last thoughts round out the work.

To create consistent power from the solar PV panel, the research study (Tafti et al., 2018) suggested a novel method that can easily calculate the voltage reference of the solar PV panel. The suggested strategy, which is a variation of the P&O method, can shift the operation point to the MPP's right or left side. This methodology avoids changing the DC-DC converter's controller during CPG operation, in contrast to existing approaches. A hysteresis band controller is recommended and can be used with both single-stage and two-stage PVPPs to generate a quick dynamic response and low-power oscillation. Simulated and experimental validation was performed to evaluate the algorithm's generality and suitability for various PVPP topologies, irradiance, and power reference curves. By permitting the point of operation to be shifted to either the right or left side of the MPP, the proposed method's key innovation is its appropriation to both single-stage and two-stage PVPPs. The CPG control, also known as power curtailment, is attained in (Sangwongwanich et al., 2018) by altering the MPPT algorithm at the level of the PV inverter. In this method, the PV system runs in MPPT mode and injects the most power possible until the set-point P_{limit} is reached. In (Ahmed et al., 2013), which also offers a recommended algorithm based on a variable-step incremental conductance approach with direct duty ratio change, the FPPT methods utilized in PV generators are explored. The technique aims to improve convergence by tuning two key parameters: the time between perturbations and the size of each perturbation in terms of the duty ratio of the dc/dc boost converter. The study creates a design technique based on a dynamic model of the system to improve the performance of the program.

FPPT and CPG methods for PV systems have been categorized into five groups in this research work based on their operational characteristics and ability to handle PSC. Left-side operation techniques offer slower transitions but enhance accuracy, as a unit change in the operating voltage results in minor variations in PV power, ensuring precision is not compromised. However, higher current in the left region, where the operating voltage is lower, leads to increased ohmic losses. On the other hand, right-side operation methods provide faster transitions with reduced losses, making them ideal for high-irradiance regions. With higher operating voltage on the right side, lower current results in lower ohmic losses, rendering it an optimal region for PV power tracking. Techniques capable of operating on either side of the MPP offer versatility but may entail more complex implementation. Methods capable of performing under PSC ensure durability and effectiveness in MPP tracking despite shading, while those unable to perform under such conditions are efficient in standard scenarios but may encounter challenges in shaded environments. The advantages of left and right-side operation methods include their respective benefits in terms of transition speed and ohmic losses, while both side operation techniques offer adaptability to varying conditions. However, all three categories may suffer from increased complexity and potentially higher implementation costs due to algorithm sophistication. Methods able to perform under PSC provide essential resilience against shading, ensuring optimal power production even in challenging environments, but at potentially higher complexity and cost. Conversely, techniques unable to perform under PSC may offer simplicity and lower costs but lack the resilience needed for shaded conditions. In practical applications, left and right-side operation methods are suitable for regions with predictable irradiance patterns, while both side operation and PSC-capable techniques are essential for areas prone to shading. Ultimately, the choice of the FPPT or CPG method depends on the specific requirements of the PV system, balancing factors such as performance, complexity, cost, and environmental conditions.

3. Comparative study of the FPPT algorithms

In this research work, we conducted a comprehensive comparative study by analyzing thirty-three relevant works focusing on FPPT Techniques and CPG Methods published in the last 10 years. This approach was undertaken to exclude outdated works on the relevant topic, ensuring the inclusion of contemporary research. Some of the works were excluded due to unclear results and methods, while others were omitted because their content overlapped with included studies. Additionally, applications-based works were not considered for the review, as their focus was primarily on the applicability of methods rather than the performance evaluation of algorithms. Each method evaluated in the analysis exhibits specific strengths and weaknesses. Some techniques excel in providing fast-tracking speed but may have higher error rates, leading to reduced overall performance efficiency. On the other hand, other methods demonstrate higher efficiency due to their low tracking error and minimal steady-state oscillations, but they may not be as effective in quickly tracking the power reference point. Furthermore, various strategies exhibit diverse performances under the PSC, with some performing well and others facing challenges in reaching optimal performance. Additionally, certain FPPT methods exhibit versatility by functioning effectively on either side of the MPP, while others demonstrate better performance specifically on the left or right side. Moreover, advanced FPPT methods identified in the literature combine efficiency with faster response rates. Nevertheless, it is important to note that these advanced techniques tend to be more complex and cost-intensive to implement compared to conventional approaches.

The thirty-three research studies have been reviewed based on

Table 1
Performance analysis of different FPPT and CPG techniques.

Year Published	Paper Ref.	Tracking Speed	Tracking Error	Operation Side	Oscillation	Efficiency	Complexity	Tested with Grid?	Operable under PSC?
2013	(IEEE Staff , 2013)	Very High	High	Right	High	Medium	Low	No	No
2013	(Ahmed et al., 2013)	Low	High	Both	High	High	High	No	No
2013	(IEEE Industry Applications Society., 2013)	Very High	High	Right	Low	Medium	High	No	No
2014	(Yang et al., 2014b)	Medium	Very High	Right	Medium	Low	High	No	No
2014	(Yang et al., 2014a)	Medium	Very High	Right	High	Low	High	Yes	No
2015	(Tang et al., 2015)	High	Medium	Right	Low	High	Low	Yes	No
2015	(Yang et al., 2017)	High	High	Both	High	Medium	High	No	Yes
2016	(Sangwongwanich et al., 2016)	High	Low	Left	Low	High	Medium	Yes	No
2016	(Tafti et al., 2016)	Medium	Very High	Both	High	Low	Low	Yes	No
2017	(Tafti et al., 2017)	Low	High	Both	High	Medium	Very High	Yes	No
2017	(Sangwongwanich et al., 2017b)	Medium	Medium	Both	High	High	High	Yes	No
2018	(Batzelis et al., 2018)	Low	Medium	Right	Low	High	Medium	No	Yes
2018	(Tafti et al., 2018)	Low	Low	Both	Low	High	Very High	No	No
2018	(Sangwongwanich et al., 2018)	Low	High	Right	Very Low	Medium	High	Yes	No
2019	(Tafti et al., 2019b)	Low	Very High	Both	Medium	Low	Medium	Yes	No
2019	(Tafti et al., 2019a)	Very High	Very High	Right	High	Low	High	Yes	No
2019	(EEE Industrial Electronics Society, 2019)	Very High	High	Both	Low	Medium	High	Yes	No
2021	(Gomez-Merchan et al., 2021)	Low	High	Both	Low	Medium	Medium	Yes	No
2021	(Kumaresan et al., 2021b)	Very High	High	Both	Very Low	Medium	High	Yes	No
2021	(Zhu et al., 2021)	Medium	High	Left	Very Low	Medium	High	No	No
2021	(Xie and Wu, 2022)	High	Low	Both	Low	Very High	Very High	No	Yes
2021	(Verma et al., 2021)	Medium	Medium	Both	Low	High	Low	No	Yes
2022	(Paduani et al., 2022)	High	Low	Both	Low	High	High	No	No
2022	(Tafti et al., 2022)	Low	High	Both	High	Medium	Low	Yes	Yes
2022	(Dehghanitafti et al., 2022)	High	Low	Both	Low	High	Medium	Yes	No
2023	(Bi et al., 2023a)	Low	Low	Left	Low	Very High	Medium	No	No
2023	(Yan et al., 2023)	Low	Medium	Both	High	High	Medium	No	No
2023	(Kolakaluri et al., 2023)	Medium	Very High	Both	Low	Low	Very High	No	Yes
2023	(Narang et al., 2023)	Medium	Medium	Both	Low	High	High	Yes	Yes
2023	(Ahmed et al., 2023b)	Very High	Low	Left	Low	Very High	Low	No	Yes
2023	(Kumaresan et al., 2023)	Medium	High	Both	Very Low	Medium	Low	Yes	Yes
2023	(Lei et al., 2023)	Low	Low	Both	Low	High	High	Yes	Yes
2023	(Bi et al., 2023b)	High	Medium	Left	Low	High	High	Yes	Yes

various criteria, which are compiled in Table 1 to thoroughly evaluate the performance of the investigated FPPT approaches. A clearer understanding of the sequential development of traditional FPPT approaches over time is made possible by the chronological grouping of the research papers by the years of their publications. In the table, the performance of the discussed literature works on FPPT and CPG methods in solar PV systems has been evaluated based on parameters such as tracking speed, tracking error, selection of the side of the operation, steady-state oscillations, efficiency, complexity of the algorithm, experimentation with the grid, and performance under the PSC. We have categorized the numerical values into different sections and put them in Table 1 instead of the numerical values. The tracking speed is marked as "very high" if the tracking time is less than 1 second (<1), "high" when it is between 1 and 2 seconds, "medium" when it's between 2 and 3 seconds, and "low" when it is greater than 3 seconds. However, the tracking error has been marked "very high" when the percentage error of the algorithms is greater than 6 %, "high" when it is between 4 % and 6 %, "medium" when it is between 2 % and less than 4 %, and "low" if it is less than 2 %. If the efficiency is higher than 99 %, it is marked as "very high", for efficiency higher than 97 % and less than 99 %, it is given "high" in the performance evaluation. When it is higher than 95 % and less than 97 %, it is marked as "medium", and it is marked as "low" if the efficiency is less than 95 %. The algorithm complexity has been categorized as "low" for the least complex method, "medium" for

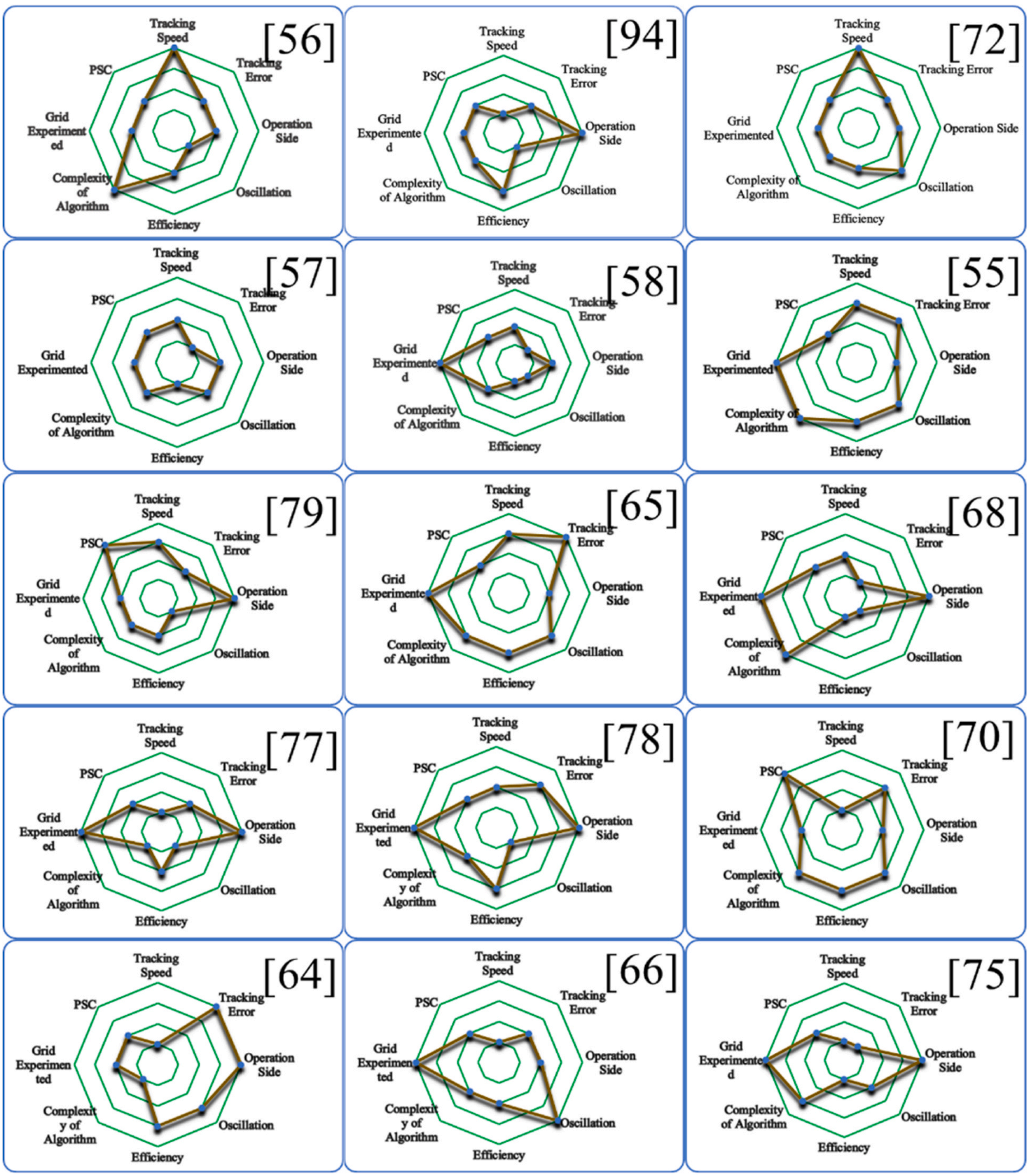

Fig. 7. Performance evaluation of the FPPT and CPG-based literature work.

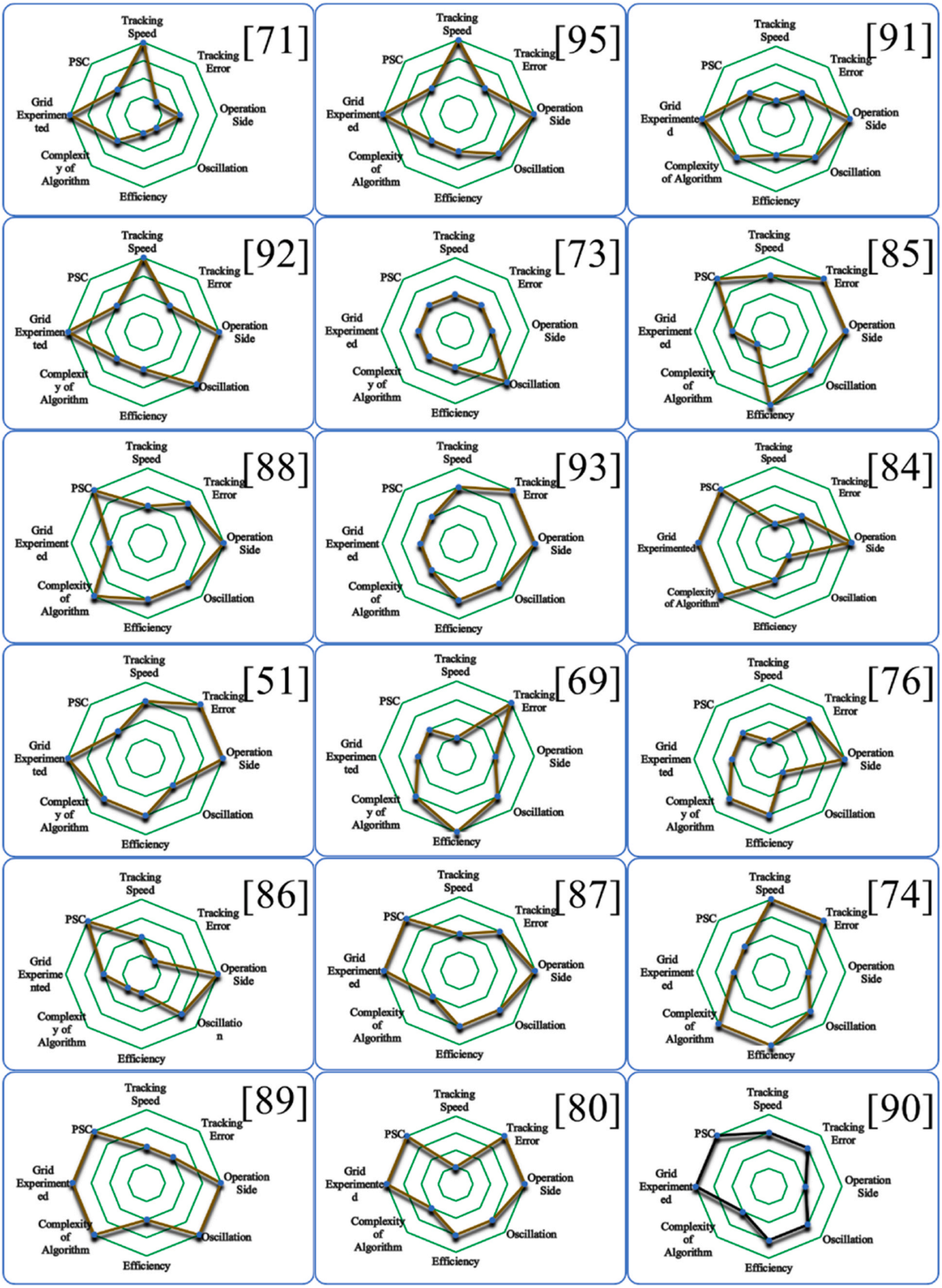

Fig. 7. (*continued*).

slightly complex algorithms, "high" if the algorithm complexity is notably high, and "very high" when the algorithm complexity is considerably high and involves multiple processes.

Eight crucial factors have been taken into account for a simplified comparison using a radar chart: tracking error, operational side, oscillations at steady-state, overall efficiency, complexity of the method, grid experimentation, and performance under the PSC (Yang et al., 2020, 2019a, 2019b). Fig. 7 presents the radar chart diagram illustrating the performance of the thirty-three FPPT and CPG methods based on these parameters. The scale range in the radar diagram ranges from 1 to 4, with methods scored accordingly. For instance, methods with "very high" tracking speed are assigned the maximum value (~4), while those with "low" tracking speed are given the minimum value (~1). Similarly, tracking error is scored in reverse order, with "very high" tracking error receiving a score of (~1) and "low" tracking error scoring (~4). Methods that perform on one side of the MPP only are assigned a value of (~2) in the radar diagram, whereas methods capable of functioning on either side of the MPP are given (~4). Tracking error percentage is utilized to evaluate efficiency since detailed information on efficiency evaluation is not consistently provided in the literature except for a few. Efficiency ratings are similarly scored from low to very high, following the same approach as the tracking speed evaluation. The efficiency of "very high" scores (~4), whereas low scores as (~1). Steady-state oscillations are scored with values of (~4) for low oscillations, (~3) for medium oscillations, (~2) for high oscillations, and (~1) for very high oscillations. Finally, the radar chart also considers whether the methods have experimented with grid integration and whether they can perform under PSC. In the chart, methods meeting these criteria are labeled "Yes" and assigned a score of (~4). On the other hand, the methods that fail to meet the criteria are labeled as "No" with an assigned score of (~2). By employing these comprehensive evaluations and the radar chart representation, we aim to provide valuable insights into the performance of FPPT methods, contributing to the advancement of power-tracking strategies in PV systems.

4. Recommendation

Assessing all the discussed methods based on multiple parameters can be challenging as each method may outperform others in certain aspects. The methods have been assigned scores according to their performance in each parameter to facilitate a comprehensive evaluation. These scores are then combined to calculate cumulative scores for each method. Consequently, the methods are categorized into four distinct groups based on their cumulative scores, as shown in Table 2. This approach allows for a more nuanced comparison, considering the overall performance of each method across multiple criteria. The research uses this scoring methodology to provide a thorough and impartial evaluation of the various FPPT and CPG approaches in solar PV systems, taking into account their advantages and disadvantages concerning key performance indicators.

Identifying specific scenarios for different method categories proves challenging due to each method's unique strengths and weaknesses. Nonetheless, methods categorized under Category A, characterized by the highest scores, typically outperform those in the lower-scoring categories (B, C, and D) across various applications. Among the evaluated methods, Category A comprises papers that have shown superior performance across most features, receiving an overall performance score of 25 or higher, as indicated in Table 2. Although methods classified under Categories B, C, and D may have lower overall performance scores, they remain valuable assets within educational and research spheres. The methods put in category A have scored highest in various criteria: accuracy, speed, selection of operating region, operation under PSCs, oscillation, and algorithm complexity. Those in category A exhibit good performance across most of these criteria and are well-suited for diverse applications, such as installing solar PV systems where maximizing efficiency and reliability are paramount. Notably, among the seven papers in Category A, (Kumaresan et al., 2023) stands out with an exceptional performance score of 26, arguably making it the best method according to this assessment approach. The other methods that fall in Category A scored a total score of 25 each. In contrast, literature works employing conventional tracking algorithms for power reference point tracking demonstrated fast tracking but suffered from inaccuracy, resulting in high tracking errors and low efficiency, leading to the lowest cumulative scores (Category B, C, or D). The FPPT technique proposed in (Kumaresan et al., 2023) is an improved version of the secant-based FPPT technique utilized in (Kumaresan et al., 2021b). This modified approach effectively overcame the limitations of its predecessor and demonstrated better performance in terms of algorithm complexity. Additionally, (Kumaresan et al., 2023) showcased the ability to perform well under PSC, a capability lacking in the previous method, which hindered its performance under such circumstances.

The critical perspective and challenges of the study topics have been elaborated hereunder:

- Performance under PSC: FPPT methods must contend with partial shading scenarios, where certain parts of the PV array receive less sunlight than others. While some FPPT algorithms excel in such conditions, accurately tracking the reference power (Pref) becomes challenging when shading occurs. This means the system might not collect as much energy as it could, making it less efficient.
- Complexity and cost: Implementing FPPT algorithms, especially those capable of operating on both sides of the MPP, can be complicated. These methods often require sophisticated control systems and algorithms, increasing the complexity of PV systems. It's really important to handle this complexity well to make sure FPPT systems are installed, operated, and maintained correctly.
- Accuracy and speed trade-off: Achieving a balance between tracking accuracy and speed is a common challenge for FPPT methods. Some algorithms prioritize rapid tracking responses to quickly adapt to changing environmental conditions. But this might mean the tracking isn't as accurate, so the system doesn't get the best power it could. Conversely, methods focusing on accuracy may exhibit slower response times, potentially missing out on transient power fluctuations.
- Robustness: FPPT methods need to demonstrate robust performance under diverse operating conditions. This includes variations in temperature, irradiance levels, and grid voltage fluctuations. Ensuring robustness is critical for maintaining stable operation and

Table 2
Categorization of FPPT and CPG techniques based on performance.

Category Name	Overall Score	Paper Reference	Total Papers
Category A	25 and above	(Dehghanitafti et al., 2022; Ahmed et al., 2023b; Lei et al., 2023; Xie and Wu, 2022; Narang et al., 2023; Verma et al., 2021; Kumaresan et al., 2023)	7
Category B	22–24	(Sangwongwanich et al., 2016; Tafti et al., 2017, 2022; Bi et al., 2023b; Kumaresan et al., 2021b; Paduani et al., 2022; EEE Industrial Electronics Society, 2019)	7
Category C	19–21	(Tafti et al., 2018; Sangwongwanich et al., 2018; Tafti et al., 2016; Bi et al., 2023a; Batzelis et al., 2018; IEEE Industry Applications Society., 2013; Yan et al., 2023; Sangwongwanich et al., 2017b; Yang et al., 2017; IEEE Staff, 2013; Gomez-Merchan et al., 2021)	11
Category D	18 and below	(Yang et al., 2014a; Tafti et al., 2019a; Yang et al., 2014b; Zhu et al., 2021; Tafti et al., 2017; Kolakaluri et al., 2023; Ahmed et al., 2013)	8

maximizing energy yield, particularly in dynamic environments where conditions can change rapidly.

- Hardware requirements: Some FPPT methods need special equipment like sensors, controllers, and actuators. Adding these to solar panel systems can make them more expensive and complicated, especially if you're fitting them into systems that are already set up. Compatibility with different PV system configurations and scalability across various applications are important factors to consider when selecting FPPT solutions.
- Scalability and adaptability: FPPT methods should be scalable and adaptable to different PV system sizes, configurations, and environmental conditions. Making sure they can be used in lots of situations means testing them thoroughly. And they should also be able to handle upgrades and changes in the future to keep working well for a long time.
- Maintenance and reliability: FPPT methods need to last a long time and not need much fixing. The parts should be strong enough to handle tough weather and work well for a long time. It's important to have good maintenance and monitoring to keep the system working well and avoid problems.

5. Conclusion

In this comprehensive comparative work, we have examined various FPPT algorithms from the literature. Each algorithm was meticulously described to provide a detailed understanding of its working principles and tracking performance under diverse operational conditions. From this extensive analysis, valuable insights and trends have emerged, enabling us to draw essential conclusions. The study has highlighted a significant observation regarding the tracking response of FPPT strategies in relation to the MPP of PV systems. Notably, the right region of the MPP exhibits rapid tracking response due to the PV curve's right side having a higher slope than the left. Due to the benefits of quicker tracking and taking less time to determine the reference voltage, several approaches have a tendency to favor performing on the right of the MPP. Furthermore, the review brought attention to the diverse capabilities of the evaluated methods concerning their performance under varying environmental conditions. While some methods demonstrate proficiency in handling sudden irradiance and temperature changes, others exhibit adaptability to PSCs. Consequently, the selection of the most suitable method becomes contingent upon the specific application requirements, necessitating careful consideration of the operational environment. The findings from this comparative study provide researchers and engineers with crucial guidance in choosing the appropriate FPPT algorithm or CPG method tailored to their intended application. This evaluation effort is an invaluable resource and baseline for future research and development as the solar energy industry develops.

6. Future studies

The review of FPPT and CPG methods reveals that no single method is perfect in all aspects. Some methods deliver fast-tracking responses, while others perform better under varying atmospheric conditions. Certain papers present methods that efficiently combine fast-tracking speed and the ability to perform under PSC, but these methods may have complex implementations. Therefore, selecting the most suitable method depends on the specific application requirements. Drawing from the insights in this review, here are some recommendations for future studies. These recommendations aim to guide future research endeavors in developing and refining FPPT and CPG methods, fostering innovation and advancement in the field.

- Identify application-specific requirements: It's imperative to thoroughly assess the application's particular requirements before settling on a method. This involves comprehensively understanding various factors, such as response time and performance in diverse atmospheric conditions. For instance, if the application prioritizes the precision of results over response time, it becomes essential to identify and prioritize methods that excel in tracking accuracy. By aligning the chosen method with the specific needs and objectives of the application, we can ensure optimal performance and effectiveness in achieving desired outcomes.
- Explore method combinations: Explore combinations of methods that achieve a balance between rapid tracking speed and resilience in challenging conditions. Investigate how these combinations can be implemented efficiently without overly complex designs. An example of such method combinations is found in the work proposed in (Paduani et al., 2022). In this study, the author introduced a hybrid approach that combines hill climbing and PSO techniques. This combined method enhances efficiency and accuracy in tracking results, effectively avoiding the trapping of local maximum power points under PSC—a challenge traditional techniques often struggle with.
- Enhance existing methodologies: Delve into ways to improve the performance of existing methods, especially concerning established standards. For instance, the modification proposed in (Yang et al., 2019a), building upon the groundwork of [92], showcases how enhancements can adapt methods for inconsistent weather conditions like partial shading.
- Acknowledge trade-offs: Recognize that no single method is perfect and be prepared to accept trade-offs. Prioritize factors critical to your application while being open to compromises in other areas.
- Benchmarking and validation: Ensure that any new methods or enhancements undergo thorough benchmarking and validation against existing standards to validate their efficacy and reliability.

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CRediT authorship contribution statement

Sajib Ahmed: Writing – review & editing, Writing – original draft. **Mehdi Seyedmahmoudian:** Validation. **Alex Stojcevski:** Validation. **Obaid Alshammari:** Writing – review & editing. **Maaz Nusrat:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Saad Mekhilef:** Supervision. **Marizan Mubin:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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