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A Comprehensive Review of Most Competitive Maximum Power Point Tracking Techniques for Enhanced Solar Photovoltaic Power Generation

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ABSTRACT

A major design challenge for a grid-integrated photovoltaic power plant is to generate maximum power under varying loads, irradiance, and outdoor climatic conditions using competitive algorithm-based controllers. The objective of this study is to review experimentally validated advanced maximum power point tracking algorithms for enhancing power generation. A comprehensive analysis of 14 of the most advanced metaheuristics and 17 hybrid homogeneous and heterogeneous metaheuristic techniques is carried out, along with a comparison of algorithm complexity, maximum power point tracking capability, tracking frequency, accuracy, and maximum power extracted from PV systems. The results show that maximum power point tracking controllers mostly use conventional algorithms; however, metaheuristic algorithms and their hybrid variants are found to be superior to conventional techniques under varying environmental conditions. The Grey Wolf Optimization, in combination with Perturb & Observe, and Jaya-Differential Evolution, is found to be the most competitive technique. The study shows that standard testing and evaluation procedures can be further developed for comparing metaheuristic algorithms and their hybrid variants for developing advanced maximum power point tracking controllers. The identified algorithms are found to enhance power generation by grid-integrated commercial solar power plants. The results are of importance to the solar industry and researchers worldwide.

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1. INTRODUCTION

Fossil fuels are of serious environmental concern due to resulting pollution and greenhouse gas emissions, whereas renewable energy sources offer clean, sustainable alternatives (Al Garni & Awasthi, 2017; Al Garni, Awasthi, & Ramli, 2018). Renewable energy sources contribute to about 25% of electricity production worldwide(REN21, 2018). Solar PV is a promising technology due to a substantial reduction in module costs and performance improvement over the last decade. The global PV capacity is expected to grow to 1582.9 GW by 2030 following a significant capacity addition by top countries worldwide, whereas 77 countries have committed to reducing carbon emissions to zero by 2050 (REN21, 2018). PV system efficiency depends on the solar cell technology used and the design of the system (Al Garni et al., 2018; Al Garni, Awasthi, & Wright, 2019; Pakkiraiah & Sukumar, 2016). The importance of site-specific optimum tilt angle for maximum solar radiation capture is described in an extensive review by Yadav and Chandel (Yadav & Chandel, 2013). However, it is also significant to extract the maximum power under intermittent irradiance, varying load, temperature, and shading conditions. The maximum power point (MPP) varies with time, fluctuating irradiance on sunny, cloudy, or partial shading conditions. PV shading in a string causes multiple maxima in the power-voltage characteristics resulting in developing hotspots that damage PV modules. Although several MPPT algorithms and controllers are used in PV systems, their effectiveness in power point tracking during varying sunny, cloudy, and partial shading conditions (PSC) is of concern, especially for large PV power plants. Thus, competitive techniques must be identified to ensure power point tracking accuracy, tracking time, cost-effective hardware, and implementation complexity. A photovoltaic power plant must generate the maximum power under varying loads, irradiance, and outdoor climatic conditions, for which MPPT algorithm-based controllers are utilized to extract the maximum available power.

The main objective of the study is to present an updated review to identify the most advanced and competitive experimentally validated MPPT algorithms for enhancing PV power generation under all types of varying climatic conditions.

1.1. Identification of Research Gaps

In early studies, Rawat and Chandel (Rawat & Chandel, 2012, 2013b) presented a review of classical and advanced MPPT techniques for PV systems. Recent work by Mao et al.

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(Mao et al., 2020) concentrated on traditional, fuzzy logic, neural networks, and hardware control methods under PSC. A detailed study using 27 different MPPT techniques under uniform and PSCs was also carried out (Pathak, Yadav, & Alvi, 2020).

The advanced metaheuristic techniques are classified as standalone metaheuristic techniques using only one algorithm and hybrid metaheuristic techniques which are further classified as homogeneous and heterogeneous. The homogeneous techniques combine two or more metaheuristic techniques, whereas heterogeneous techniques combine two different types of algorithms.

In a review study, Katche et al.(Katche, Makokha, Zachary, & Adaramola, 2023) considered only six metaheuristic algorithms and five hybrid algorithms. Metaheuristic algorithms hybridized with other metaheuristic algorithms are not considered. Troudi *et al.* (Troudi et al., 2022) did not consider metaheuristic or hybrid intelligent algorithms. Only five algorithms, namely P&O, INC, and ANN-based methods, were considered. Başoğlu (Başoğlu, 2022) did not consider traditional or metaheuristic algorithms and, instead, focused only on hardware approaches in the MPPT, whereas Ahmed et al. (S. Ahmed, Mekhilef, Mubin, & Tey, 2022) reviewed the performances of six conventional algorithms.

Various other authors have also reviewed MPPT (Bendib, Belmili, & Krim, 2015; Eltawil & Zhao, 2013; Gupta, Chauhan, & Pachauri, 2016; Jordehi, 2016; L. Liu, Meng, & Liu, 2016; Rezk & Dousoky, 2016; Salam, Ahmed, & Merugu, 2013; Sinha & Chandel, 2015; Verma, Nema, Shandilya, & Dash, 2016) and metaheuristic techniques (Abu Eldahab, Saad, & Zekry, 2014; Ali et al., 2020; Belhachat & Larbes, 2018, 2019; Hanzaei, Gorji, & Ektesabi, 2020a; Lian L. Jiang, Srivatsan, & Maskell, 2018; G. Li, Jin, Akram, Chen, & Ji, 2018; Mohapatra, Nayak, Das, & Mohanty, 2017; M. Seyedmahmoudian et al., 2016; B. Yang et al., 2020); however, the latest metaheuristic algorithms and their hybrid variants remain unexplored. Different algorithms and techniques have been proposed to overcome the tracking problem of MPP under varying conditions. The highlights and limitations of the latest reviews on MPPT techniques under PSCs are summarized in Table 1. It is clear from Table 1 that most of the recent review papers have not covered metaheuristic and hybrid techniques, except for reference (Belhachat & Larbes, 2018). However, the authors did not identify the most competitive techniques. The research gaps identified are drawn from the literature:

- Most of the researchers have reviewed different algorithms but did not identify the most competitive techniques for MPPT which can be used for industrial applications.
- All conditions (varying load, irradiance, and other outdoor climatic conditions) that can affect the behavior of the algorithms should be considered for validation.
- Simulated studies are required to be validated by experimental studies to ensure the capability of the methods under real outdoor conditions.
- Factors such as complexity, accuracy, convergence speed, and stability need to be considered for comparison between the available techniques.

Table 1. Research highlights and outcomes of recent reviews on MPPT techniques

No.	Reference	Highlights	Research Outcome
1	Ramli et al. (2017) (Ramli, Twaha, Ishaque, & Al-Turki, 2017)	A review of 4 conventional and 11 soft computing methods for MPPT was presented. ANN, Fuzzy Logic, and some metaheuristic methods were analyzed. Many evaluation metrics were considered for evaluation.	Researchers concentrated on the use of MPPTs under PSCs during the last few years. A robust MPPT algorithm must be used to enhance PV power production. PSO-based techniques were found to be better in searchability and convergence speed as compared to the other reviewed techniques.
2	Belhachat & Larbes (2018). (Belhachat & Larbes, 2018)	A review of 16 metaheuristics 19 hybrids, 3 mathematically based, and 9 other GMPPT techniques was given.	Modified techniques outperformed original ones. Hybrid methods overcame the original methods in terms of stability, speed, and efficiency.
3	Li et al .(2018) (G. Li et al., 2018)	A review of 3 evolutionary algorithms and 5 swarm intelligence-based algorithms was conducted.	GA and PSO were the most used techniques in literature; however, differential evolution was the simplest technique. Standalone techniques can be improved by combining them with conventional techniques; Swarm intelligence-based methods were better than evolutionary ones
4	Belhachat & Larbes (2019) (Belhachat & Larbes, 2019)	A comparison of 11 optimization algorithms; 11 hybrids; 6 exploitation of characteristic curves based; and 6 other techniques was provided.	Enhanced techniques exhibited better performance than the original ones. Hybrid techniques were found to be more suitable for MPPT.
5	Hanzaei et.al. (2020) (Hanzaei et al., 2020a)	A review of conventional, novel, and hybrid techniques was given. Many metrics were considered for evaluation.	Modified hybrid MPPT techniques demonstrated exceptional accuracy in MPPT algorithms, requiring intricate computations and incurring a higher implementation cost.
6	Ali, et al. (2020)(Ali et al., 2020)	Comparison of 11 conventional and 15 soft-computing MPPT algorithms was presented; GMPP finding, convergence speed, design complexity, and sensitivity were considered.	Under changing shading conditions, classical algorithms did not succeed in finding the MPP. Although soft computing algorithms performed better under unpredictable conditions, they were too complex and difficult to implement.

* *In this table "hybrid" techniques cover both heterogeneous and homogeneous.*

1.2. Methodology

The methodology employed in crafting this review paper involved a systematic and thorough approach. The initial phase focused on conducting an extensive literature review to identify and collect relevant research articles, conference papers, and scholarly publications related to maximum power point tracking (MPPT) techniques in solar photovoltaic (PV) power generation. The scope was carefully defined to include the most recent and impactful contributions in the field. Following the literature review, a categorization framework was established to organize the various MPPT techniques based on their working principles and methodologies. The paper then proceeded to present a detailed discussion of each technique, analyzing their strengths, weaknesses, and applications. Comparative analyses were conducted to evaluate the competitiveness of these techniques, taking into account factors such as efficiency, response time, and adaptability to different PV scenarios. Throughout the process, meticulous attention was paid to maintaining a coherent and logical structure, ensuring that the study provides a comprehensive and insightful overview of the state-of-the-art in MPPT techniques for enhanced solar PV power generation.

1.3. Citation Analysis: Mapping the influence and impact

In conducting a citation analysis for this comprehensive survey paper, a total of 169 papers have been meticulously examined. Among these, 147 are published in international journals of repute, showcasing a strong foundation in peer-reviewed literature. Notably, 14 papers have made their mark in conference proceedings, underscoring active participation in academic discourse. Furthermore, the survey incorporates insights from 2 reports, 3 book chapters, and contributions to 3 symposiums and workshops, reflecting a diverse engagement with scholarly forums. The analysis unveils that "Renewable and Sustainable Energy Reviews" stands out as the highest-cited journal, with an impressive 21 citations. Publishers also play a crucial role, with Elsevier emerging as the most cited, with a total of 60 citations, followed by IEEE with 21 citations. Other significant contributors include John Wiley and Sons, Hindawi, MDPI, and a range of esteemed publishers, each adding distinct perspectives to the overarching narrative. This citation analysis serves as a comprehensive overview of the scholarly impact and influence of the surveyed material, revealing the multifaceted engagement within the academic community.

1.4. Novelty and Contribution

Based on these research gaps in the literature and recent reviews, an updated comprehensive analysis of 14 different metaheuristic algorithms, their improved versions, and 17 hybrid MPPT techniques for optimized solar power generation are presented, and the most competitive techniques were identified based on experimental studies only. These models can be utilized for various industrial applications because they operate accurately and swiftly under all conditions. They have undergone experimental testing in real-world conditions.

The novelty of the present study is as follows:

- This study focuses on metaheuristic and hybrid (homogeneous and heterogeneous) techniques due to their impressive performance considering accuracy, speed, complexity, and the minimum required facilities for implementation.
- Although several studies are carried out in MPPT using metaheuristic algorithms, the information on these studies is dispersed and has not been critically analyzed, which is more relevant in the present PV power generation scenario.
- This study also explains techniques in detail and highlights experimentally validated research.
- This work is important not only for researchers in the future to find a starting point for their research but also for the solar industry to further develop innovative Maximum Power Point Tracking (MPPT) controllers with improved tracking capabilities.

The article is structured as follows: Section 2 provides an overview of the Maximum Power Point Tracking (MPPT) problem. In Section 3, we delve into an overview of standalone metaheuristic techniques employed for MPPT. Section 4 focuses on discussing heterogeneous hybrid methods for achieving global MPPT (GMPPT) in a Photovoltaic (PV) system. Moving on to Section 5, we analyze homogeneous hybrid methods. The outcomes, coupled with subsequent research, are thoroughly examined in Section 6, while Section 7 encapsulates the drawn conclusions.

2. OVERVIEW OF MAXIMUM POWER POINT TRACKING OF PV SYSTEMS

2.1. MPPT Controller-basics

MPPT is an electronic circuit that finds a match between PV modules and converter to extract maximum power (P_{max}) and is used in combination with DC-DC converters (Figure 1).

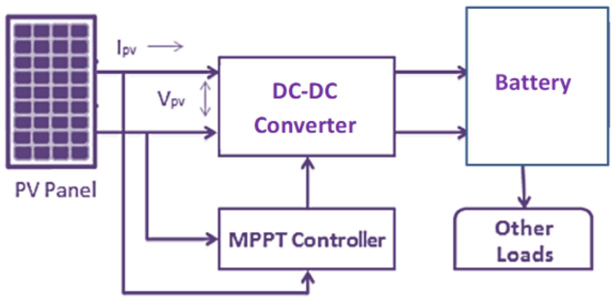

Figure 1. MPPT controller for maximum power extraction from a PV panel

Recent studies have concentrated on enhancing the performance of PV panels to obtain maximum power using different techniques and designs (Abu Eldahab et al., 2014; Eltawil & Zhao, 2013; Ram, Babu, & Rajasekar, 2017; Ramli et al., 2017; Rezk & Dousoky, 2016; Verma et al., 2016). Since the relation between the voltage (V) and current (I) is nonlinear, the power generated from a PV system could deviate from the MPP, as shown in Figure. 2. Such mismatch is caused by the variation in solar irradiation, air temperature, solar cell area, and load (Bendib et al., 2015).

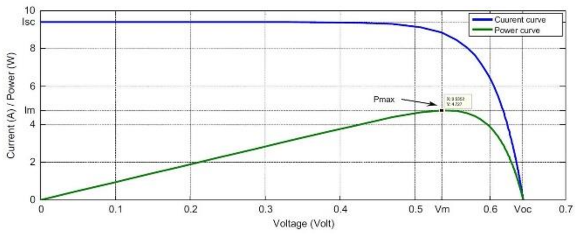

Figure 2. I-V and P-V characteristics of solar cells under uniform conditions (Verma et al., 2016)

The duties of the MPPT controller are to overcome this issue by tracking the MPP under all conditions. It will adjust the operating point (voltage/current) to harness more power. Conventional techniques use simple algorithms that can ascend the power line shown in the graph until it reaches the peak, which becomes the new operating point at which the module will generate MPP. However, the PV array could be partially shaded due to clouds, trees, nearby buildings, or even dust on the PV surface.

As shown in Figure 3, PSC makes I-V and P-V characteristics more complicated since several peaks occur instead of a single peak under uniform conditions. This complexity makes the MPPT task more challenging for conventional techniques, which are likely to be trapped in a local maximum (another peak value). Therefore, new techniques must be developed to search for the optimal point at which the system should operate.

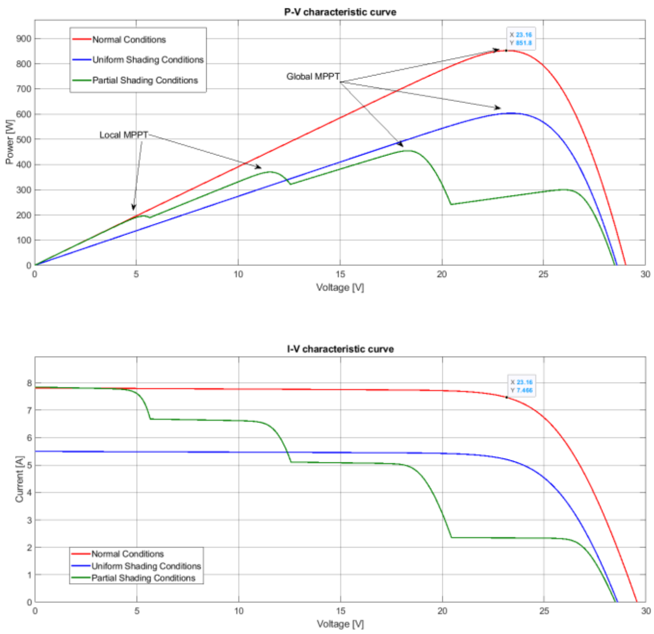

Figure 3. P-V and I-V characteristics under uniform and partial shading conditions at STC

2.2. Overview of Metaheuristic algorithms for MPPT

In this section, an updated literature review of metaheuristic techniques is presented. MPPT techniques are categorized into conventional and soft computing (SC) techniques. The conventional techniques include Hill Climbing (HC), Incremental Conductance (IC), and Perturb and Observe (P&O) methods. A review of HC techniques is presented in (Rawat & Chandel, 2013a). The conventional techniques are implemented to find the maximum value when only one peak exists; as such, they fail to identify the MPP of the system in case of multiple peaks and may get stuck in the first peak, which could be a local maximum. Metaheuristic algorithms overcome this type of problem due to their capability to search the area of interest, especially for non-linear problems, and find the maximum (or minimum) point. These techniques are found to achieve higher efficiency, accuracy, and faster convergence under varying environmental conditions, despite being more complex compared to conventional techniques (Khare & Rangnekar, 2013).

A metaheuristic is a set of algorithmic models that can be used to describe heuristic methods applicable to a broad set of problems (Beheshti, Mariyam, & Shamsuddin, 2013). Metaheuristic methods, which can search large areas of candidates with few or no assumptions, have become popular recently and have also improved solving complex optimization problems, including wind (Dorigo & Stützle, 2004) and solar energy systems (Baños et al., 2011). The complexity and nonlinearity of solar MPPT make it difficult to use classic optimization algorithms. Population, trajectory, memory, and nature-inspired characteristics are used to classify metaheuristic algorithms. Population-based algorithms can search multiple initial points in a parallel style, whereas trajectory-based algorithms perform searches based on a single solution at a time and encompass local search-based algorithms. The use of memory is one of the most important characteristics of classifying metaheuristics. This feature can keep track of recently performed solutions and can accumulate synthetic parameters for the search.

2.3. Evaluation metrics

The following metrics are used to test the behavior of different algorithms of MPPT techniques.

- **Efficiency**: Ratio of the actual to ideal output power (Lyden & Haque, 2015b).
- **Accuracy:** The ability of the model to reach the MPP under different conditions (Belhachat & Larbes, 2018).
- **Convergence time:** The time required to reach the steady state as the model should be as fast as it can be to determine the MPP as a long convergence time leads to greater power dissipation (Ramli et al., 2017).
- **Stability in the steady state:** It defines the stability of the output around the MPP. The more oscillation occurs the more power loss.
- **Complexity:** The number of tuneable parameters in a model and the required computational operations. Due to complexity, some methods could be implemented using analog processors; however, novel methods require digital processors (Mohapatra et al., 2017).
- **Sensitivity:** The ability of the model to react fast and accurately when a tiny change happens in ambient conditions.

To compare the behavior of various algorithms, evaluation metrics should be employed. However, many researchers do not adhere to these metrics, complicating the task of comparing the performance of different techniques. Each case study has its dataset and is conducted under different environmental conditions.

To illustrate these metrics, a P&O-based MPPT PV system with 47 parallel modules, each containing 10 modules, is considered. The system utilizes a boost converter to control the generation. The PV system is simulated using MATLAB, and a P&O-based MPPT algorithm is employed to track the Maximum Power Point (MPP). The irradiance is varied rapidly to test the response of the MPPT algorithm, as shown in Figure 4(a). The actual output is represented by the blue line in Figure 4(b), while the expected output is depicted by the red line.

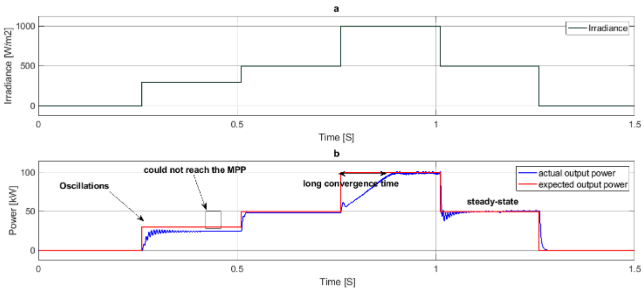

Figure 4. (a). Varying irradiance falling on PV system; (b) Output power for an MPPT P&O-based system corresponding to varying irradiance

As illustrated in Figure 4, the system output fluctuates between (0.25-0.75) and fails to attain the Maximum Power Point (MPP). Additionally, it oscillates in the steady-state, and there is a prolonged convergence time evident between (0.75-1). Consequently, the analysis of the metrics indicates that the model exhibits very low efficiency. This type of analysis can be conducted for all MPPT models.

3. OVERVIEW OF THE STANDALONE METAHEURISTIC TECHNIQUES USED FOR MPPT

In this section, all stand-alone metaheuristic techniques are reviewed.

3.1. Genetic Algorithm

GA, based on the principle of survival of the fittest, encompasses genetic operators like selection, crossover, and mutation over a series of time-steps called generations (Mitchell & Melanie, 1996). GA has been widely applied to enhance the MPPT of photovoltaic systems; however, implementing it under PSCs cannot be easily achieved by using low-cost micro-controllers (Yi Hua Liu, Chen, & Huang, 2015). The basic steps in applying GA to MPPT are described in reference (Ramli et al., 2017). Various approaches to using GA to improve the performance of power point trackers are outlined in (Beheshti et al., 2013). GA is applied solely, in hybrid combinations with conventional methods, hybrid with metaheuristic methods, hybrid with a fuzzy logic controller (FLC), and in conjunction with neural networks (Mohajeri, Moghaddam, Shahparasti, & Mohamadian, 2012; Ramaprabha, Gothandaraman, Kanimozhi, Divya, & Mathur, 2011) (Amine, Abdelaziz, & Najib, 2015; Bellala DJ, 2007; Dahmane, Bosche, El-Hajjaji, & Pierre, 2013; El-Arini, Othman, & Fathy, 2013; Maziar Izadbakhsh,Alireza Rezvani, 2015; Rezvani, Izadbakhsh, & Gandomkar, 2015; Vafaei, Rezvani, Gandomkar, & Izadbakhsh, 2015) (Hadjaissa, Ait cheikh, Ameur, & Essounbouli, 2016; Harrag & Messalti, 2015; L. Liu & Liu, 2012; Ramaprabha R, 2012). GA is combined with different techniques such as ANN (Shaiek, Ben Smida, Sakly, & Mimouni, 2013), FL (Ilyas, Ayyub, & Khan, 2020), SVM (Tian et al., 2014), PSO (Shankar & Mukherjee, 2015), etc. to boost their performance. GA-FL and GA-ANN combinations are studied in this review paper (Garud, Jayaraj, & Lee, 2021) for all PV applications. In (Messai, Mellit, Guessoum, & Kalogirou, 2011), GA was employed to overcome the difficulties in defining the optimal membership functions of the FLC, which takes a long time if the "trial & error" method is used.

GA has been applied to GMPPT and compared with conventional techniques by numerous researchers (Bellala DJ, 2007; Dahmane et al., 2013; Mohajeri et al., 2012; Ramaprabha R, 2012). Simulation studies indicate that GA outperforms P&O and IC methods under changing climatic conditions (Hadji, Krim, & Gaubert, 2011). In (Dizqah, Maheri, & Busawon, 2014), the reference voltage of the PV array is generated by perturbation, while GA is employed for heuristic search to determine the GMPP of the array (Mohajeri et al., 2012; Ramaprabha R, 2012). In (Zagrouba, Sellami, Bouaïcha, & Ksouri, 2010), however, GA was applied to obtain electrical parameters, namely photocurrent, saturation current, series resistance, shunt resistance, and ideality factor of PV modules to determine MPP. Oscillations near MPP due to the mutation are the main problems in GA. Another issue is the reinitialization of the algorithm due to sudden changes in the atmospheric conditions or shading patterns (Beheshti et al., 2013).

GA was used to find the optimal membership function of an FLC (Ilyas et al., 2020; Larbes, Aït Cheikh, Obeidi, & Zerguerras, 2009). FLC inputs include the error and the change in error (Larbes et al., 2009). The output of Fuzzy Logic is the duty cycle of the DC-DC converter. GA integration with FLC is a better option for MPPT and exhibits better than FLC and P&O techniques under different temperature and radiation conditions (Shankar & Mukherjee, 2015). Based on SVR and GA, as outlined in (Tian et al., 2014), GA was utilized to search for the best solar irradiation and air temperature as two inputs to SVR. As a result, a hybrid method was found to track the voltage at MPP accurately under changing conditions.

FLC is optimized using Genetic Algorithms (GA), which instantly and optimally select both control rules and membership functions for FLC (Ilyas et al., 2020; Messai et al., 2011). GA-FLC-based MPPT is superior to the P&O controller since it has a shorter response time and the oscillations are significantly reduced in the steady state. GA is employed to provide a reference voltage corresponding to maximum power during changing conditions for an on-grid PV system (Hadji et al., 2011). ANFIS is trained using these optimized values, and oscillations around MPP are significantly reduced

In (Mary, Kumar, Poluru, & Reddy, 2015), a scheme for an off-grid PV system with a dual DC output power supply is proposed. Genetic Algorithm ((Mary et al., 2015)GA) is employed to optimize the PID parameters to maintain a voltage of 100V, which is connected to the boost converter, while the Incremental Conductance (INC) method is utilized for the buck converter. The system's performance is evaluated under step changes in load and varying insolation conditions. GA is also applied for tuning the parameters of PID and FOPID controllers, achieving an efficiency of 99.95% and 94.02% for steady-state and dynamic-state, respectively.

A different approach to MPPT for a microgrid PV-wind hybrid system was proposed using GA for ANN training, in which case the GA optimized the data and these optimum parameters were used in ANN (Rezvani, Izadbakhsh, & Gandomkar, 2016) and models were applied using MATLAB/Simulink. GA-ANN experienced a shorter response time, higher power, greater stable MPP, and less oscillation than the P&O, IC, and fuzzy methods. However, due to potential alterations in the PV arrays' output characteristics, periodic training of the ANN is necessary.

In a PV on-grid system in the UK, GA is applied to achieve MPPT (Zhang & Bai, 2008). In this system, ANN and control of MPPT are tuned during normal plant operation and do not require prior knowledge of the system, enabling real-time MPP attainment without human intervention. Similarly, GA is employed to optimize the ANN-based MPPT algorithm for an off-grid system (Kulaksız & Akkaya, 2012). Simulation and experimental results demonstrate that the proposed method exhibits a faster response time and reduced oscillations around MPP compared to P&O. This approach eliminates the need for a DC-DC converter and its associated losses. However, a drawback of such systems is the processing burden involved in training the MLP model using GA.

Researchers introduced a GMPPT algorithm, merging a P&O algorithm with a modified GA structure to swiftly determine the MPP in partially shaded photovoltaic systems. Implemented on a DSP for a small-scale PV system, it exhibits adaptability, and efficient convergence, and future research aims to explore chaos theory for improved randomization and extend the algorithm to wind energy conversion systems.

3.2. Particle Swarm Optimization

PSO is a stochastic optimization intelligence technique based on the swarm (birds and fish) behavior, called particles (Eberhart & Kennedy, n.d.; Miyatake, Veerachary, Toriumi, Fujii, & Ko, 2011). These particles are employed to search the entire space based on the information exchanged among them (L. Liu & Liu, 2012). PSO has been the most popular metaheuristic method for MPPT in the last decade. PSO is characterized by fast response, flexibility, no steady-state oscillations, and robustness with such drawbacks as randomness of initial particles, ease of getting trapped into a local optimum, and failure to achieve MPP (K. H. Chao, 2015; Miyatake et al., 2011). PSO differs from GA in its memory system, which helps converge faster to the best option based on the fitness function. PSO is easy to implement, includes the need for a system with coordination, and may suffer from partial optimism (Farh, Eltamaly, & Othman, 2018). These drawbacks were resolved in the enhanced versions (Mirebrahimi SM, 2016; Mohammadmehdi Seyedmahmoudian et al., 2015; Mohammadmehdi Seyedmahmoudian, Mekhilef, Rahmani, Yusof, & Asghar Shojaei, 2014; Shi, Zhang, Zhang, Xue, & Yang, 2015; K. Sundareswaran, Vignesh kumar, & Palani, 2015).

A multidimensional search technique based on PSO, employed with centralized MPPT control utilizing voltage and current sensors, outperforms Hill Climbing (HC) and Fibonacci search methods. However, it is limited to systems with multiple converters (Daraban, Petreus, & Morel, 2014). A standard PSO-MPPT with direct control of the buck-boost converter was proposed to remove the PI control loop (Ishaque, Salam, Shamsudin, & Amjad, 2012). This technique improves GMPPT, eliminates unnecessary components, and enjoys high accuracy (99.5%) under PSCs. PSO was used for tuning the boost converter and the PID controller can track MPP with higher accuracy (Sarvi, Ahmadi, & Abdi, 2015). PSO algorithm in (Mirhassani, Golroodbari, Golroodbari, & Mekhilef, 2015) tuned PID controller to track MPP with higher accuracy as compared to P&O, improved P&O, and voltage and current-based MPPT. Results demonstrate that PSO has better performance, faster response, and convergence, especially under rapidly varying environmental conditions.

PSO is applied with the DC voltage superposition principle for predicting the output characteristics of a PV array under PSCs by using the least square method for curve fitting (H. Li & Liu, 2014). PSO used for MPPT improves the performance of the PV system by adjusting the duty cycle of the DC-DC converter accurately (Venugopalan, Krishnakumar, Sarjila, & Rajasekar, 2013). PSO applied for MPPT in a single-stage and single-phase on-grid system demonstrates a faster response and improved efficiency (Souamy, 2012). A comparison between conventional MPPT techniques and PSO was carried out (Ramdan A. F. Z., 2014).

The optimal interconnection of multi-junction solar cells with non-inverting buck-boost converters was considered (Pious & Rajalakshmi, 2014). Only one MPPT control was used for multiple solar modules and PSO was able to track MPP with multiple solar modules under complex illumination.

The improved PSO that incorporates a Newton interpolation method to reduce iterations and steady-state oscillations was discussed in (Wei & Li, 2022). MATLAB®/Simulink® simulations indicate that the enhanced PSO algorithm achieved superior tracking accuracy and speed compared to the conventional PSO, with an initial tracking speed increase of over 30%.

To address the limitations of conventional PSO, a novel MPPT algorithm, which is a Modified PSO with Hybrid Adaptive Local Search (MPSO-HALS), was proposed by (Koh, Tan, Lim, & Tan, 2023). HALS introduces an adaptive local search mechanism, enhancing tracking accuracy and convergence speed. The algorithm incorporates a modified initialization scheme using grid partitioning and oppositional-based learning for even population distribution. A rank-based selection method is employed, and a modified global search rapidly identifies the approximated location of the GMPP. The local search method involves Perturb and Observe with adaptive step size (P&O-ASM) to refine the duty cycle with minimal oscillations. Implemented on a low-cost microcontroller for real-time applications, MPSO-HALS outperforms other algorithms, including Bat Algorithm (BA), Improved Grey Wolf Optimizer (IGWO), conventional PSO, and Perturb and Observe (P&O). The algorithm demonstrates a convergence time under 0.3 seconds and tracking accuracy exceeding 99% across various complex PSC scenarios, showcasing its robustness and efficiency.

3.3. Improved PSO application to MPPT

A large number of particles and randomness lead to long computational time, power loss, and fluctuations, thus reducing PSO performance (Sudhakar Babu, Sangeetha, & Rajasekar, 2016). The main challenge in applying PSO is adjusting the velocity at each iteration. Low acceleration leads to slower convergence, whereas excessively high acceleration can cause the particle to escape the search space. An enhanced PSO called Adaptive Perceptive Particle Swarm Optimization (APPSO) was proposed (Roy Chowdhury & Saha, 2010). Sensors were used to control multiple PV arrays, as outlined in (Chowdhury, Mukherjee, & Saha, 2009). APPSO makes the particle movement more flexible, and the field-programmable gate array (FPGA) based implementation ensures hardware-based flexibility. Under PSCs, APPSO is shown to be 97.95% accurate in tracking MPP as compared to the PSO accuracy of 96.41%.

MPPT algorithm for a centralized PV system was implemented utilizing improved PSO (Yi Hwa Liu, Huang, Huang, & Liang, 2012). IPSO achieves better tracking than standard PSO but increases the complexity of the algorithm. To ensure direct control of the duty cycle with near-zero oscillations around the MPP, IPSO was proposed (Ishaque, Salam, Amjad, & Mekhilef, 2012), which achieved better tracking than traditional methods under PSCs; however, no guidelines for the system design were provided. IPSO was presented, considering different classifications of particles based on their amplitude (Zhao, Zhao, & Zhang, 2014). In (Shuying, Guodong, Jisheng, & Jinyu, n.d.), an IPSO was proposed where the duty cycle was divided into two stages to initialize PSO towards enhancing MPPT, which improved the accuracy.

Another developed modifies cognition factor, social factor, and weight parameters of PSO during the algorithm (K. H. Chao, 2015). In (Gokilapriya & Barvin Banu, 2015), deterministic-PSO (DPSO) was employed to eliminate randomness from the acceleration factors of the PSO velocity equation of conventional PSO. The Hybrid-PSO (HPSO) controls the divergence phenomenon of the particles known as the "explosion" of the swarm. HPSO outperforms GA and P&O in terms of convergence and stability (Shankar & Mukherjee, 2015).

DPSO for MPPT was utilized to overcome the problems related to searching and randomness associated with PSO and offered a much simpler structure than PSO (Ishaque & Salam, 2013). The simulation and experimental results using a modified PSO (MPSO) exhibited near-zero oscillations around MPP (Sudhakar Babu, Rajasekar, & Sangeetha, 2015).

Proper initial value selection by limiting the duty cycles within definite boundaries was proposed by (Sudhakar Babu et al., 2016), which demonstrates a significant ability to track the GMPP accurately with near-zero oscillations under PSCs. A modified PSO algorithm proposed by (Lal & Singh, 2016) can track the MPP for a utility-scale on-grid PV system. Another enhanced-PSO uses chaotic searching with adaptive parameters to overcome trapping in a local optimum (Hong, Beltran, & Paglinawan, 2016) and results show that it converges faster than PSO. As the number of modules increases, the MPPT system using one core becomes ineffective, since its accuracy and convergence time drop. Thus, a multicore-modified PSO for tracking control was proposed based on search-agent deployment and tracking strategy (R.-M. Chao, Nasirudin, Wang, & Chen, 2016). However, providing MPPT for each module increases the cost. Therefore, a multi-context cooperatively coevolving PSO (CCPSO-m) was proposed for a large-scale photovoltaic system (Tang, Wu, & Fang, 2016). The MPPT is usually implemented on each PV branch rather than on each module, thus allowing each module to operate on its MPP efficiently.

A control scheme for a grid-connected system, which incorporates low-voltage ride-through capabilities, was developed using IPSO (Saad, El-Sattar, & Mansour, 2016). A current calculated technique was employed along with PSO for MPPT (L. Liu, Liu, & Gao, 2013). A Lagrange Interpolation (LI) method, used to assist the PSO approach to find GMPP, was proposed by (Koad, Zobaa, & El-Shahat, 2017) that enhances tracking speed. An improved PSO was proposed by (Hayder et al., 2020) for controlling a DC-DC boost converter, which achieved more than 99% accuracy under PSCs.

3.4. PSO application with Artificial Intelligence Techniques

Being a time-invariant optimization technique, PSO cannot automatically track the changes in time under PSC. To overcome this problem, a re-initialization technique is proposed along with an FL controller to adjust the output power, voltage, and oscillations near GMPP (Farh et al., 2018). The authors (Muthuramalingam & Manoharan, 2014) adopted an experimental comparison between hybrid P&O-ANFIS and PSO-ANFIS intelligence techniques, considering different conditions (Prakash, Sahoo, Karthikeyan, & Raglend, 2015). The results indicate that this technique can find a suitable duty cycle to extract MPP under fast climatic variations.

3.5. Ant Colony Optimization

ACO mimics ant's behavior in a colony versus food source to search for an optimal solution was investigated by Macro Dorigo (Maniezzo, 1996). Using probabilistic and communications strategies, this technique is useful for finding the shortest path to a goal, represented as a path from colony to food source (Dorigo & Stützle, 2004). ACO is applicable to problems with dynamic changes, as it runs without interruption during real-time changes (Salam et al., 2013). MPPT based on ACO is proposed for large-scale systems under PSC (Lian Lian Jiang, Maskell, & Patra, 2013), where ACO feasibility is studied and shows better performance than P&O and PSO.

3.6. Artificial Bee Colony

ABC has the benefit of employing fewer control parameters (KARABOGA, 2005) as compared to GA and PSO (Karaboga & Akay, 2009). The employed, onlooker, and scouts groups are employed in ABC for different tasks. The onlooker and employed bees work in their local neighborhoods, whereas the scout bees fly and choose their food source arbitrarily. If the nectar quantity in the new site is higher than the one in their memory, they remember the new site and forget the previous one (Beheshti et al., 2013).

ABC was applied by designing an optimal PI MPPT controller and was claimed to outperform GA and open-loop at different irradiation levels (Saravanan & Ramesh Babu, 2016). An ABC algorithm developed for obtaining GMPP indicates enhanced performance as compared to PSO and enhanced P&O under PSC (Saravanan & Ramesh Babu, 2016). Another ABC-based MPPT with two control parameters was developed in (Benyoucef, Chouder, Kara, Silvestre, & sahed, 2015) to boost the convergence time.

3.7. Cuckoo Search

CS mimics the behavior of cuckoo birds, which lay their eggs in nests of other birds, in combination with the Lévy flight behavior of some birds and fruit flies (X. Yang, Deb, & Behaviour, 2009). Female cuckoos search for a suitable nest of another bird species to hatch the cuckoo eggs. If a host bird realizes the presence of other birds' eggs, it either throws them away or abandons the nest (Gandomi, Yang, & Alavi, 2013). CS requires fewer parameters fine-tuning as compared to PSO and GA (Rajabioun, 2011). CS is more suitable for medium- and large-sized PV systems than P&O and PSO (Saravanan & Ramesh Babu, 2016). Ahmed et al. (J. Ahmed & Salam, 2014) also investigated the performance of CS under different conditions and found it able to outperform P&O and conventional PSO methods with 0.000008% error and 100-250ms tracking time, in addition to low fluctuations in the steady state.

Abdulaziz et al. (Abdulaziz, Attlam, Zaki, & Nabil, 2022) addressed the challenge of enhancing photovoltaic (PV) system efficiency through maximum power point tracking (MPPT) techniques, specifically employing the cuckoo search algorithm (CSA) and particle swarm optimization (PSO). Simulations using MATLAB/Simulink with the MSX-60 PV module and boost DC-DC converter reveal that the PSO technique outperforms CSA in terms of efficiency and stability across various atmospheric conditions. The study explores the impact of different PV-array structures on MPPT efficiency, concluding that the total cross-tied (TCT) structure is the most effective, despite acknowledging challenges such as convergence speed issues and sensitivity to parameter changes in both algorithms.

3.8. Fireworks Algorithm

FWA was developed by Tan and Zhu (Tan & Zhu, 2010). Its concept mimics the shower of firework sparks that fill the local space and search around a specific point where the firework is set off. FWA can balance between exploitation and exploration. Studies using FWA-based MPPT established fast-tracking and near-zero oscillations under varying environmental conditions (Khalessi, Niroomand, Dadkhah, & Nikouei, 2020; Sangeetha, Sudhakar Babu, & Rajasekar, 2016).

3.9. Simulated Annealing

Simulated Annealing (SA) functions based on the transition of a thermodynamic system from one energy level to another (Kirkpatrick, Gelatt, & Vecchi, 1983) and is one of the most flexible algorithms among others, but requires a long processing time to obtain high-quality solutions (Emile Aarts, 2014). It converges to GMPP, avoids trapping in local maxima, and requires random numbers to be generated, which increases its complexity (Chaves et al., 2016).

3.10. Grey Wolf Optimization

A swarm intelligence technique simulates the leadership and hunting behavior of a predator species, grey wolves. This technique is based on a four-level dominance hierarchy among wolves: alpha, beta, delta, and omega (Mirjalili, Mirjalili, & Lewis, 2014). GWO MPPT demonstrates superior performance, with faster convergence to global peak, and faster PV tracking as compared to P&O and improved-PSO under partial shading and rapid irradiation changes (Mohanty, Subudhi, & Ray, 2016).

Aguila-Leon et al. (Aguila-Leon, Vargas-Salgado, Chiñas-Palacios, & Díaz-Bello, 2023) introduced an optimized Maximum Power Point Tracking (MPPT) controller based on the Grey Wolf Optimization (GWO) algorithm, outperforming traditional methods like Perturb and Observe and Incremental Conductance under various solar conditions. Comparative analysis with metaheuristic algorithms reveals the GWO-optimized controller's superior performance, yielding an average of 6% higher output power and 3% higher efficiency. The GWO algorithm demonstrates the best tuning performance with the lowest Root Mean Square Error and faster settling time, showcasing improved system response and reduced curling effect at power converter outputs.

3.11. Firefly Algorithm

FFA is inspired by the behavior of fireflies and their flashing patterns and is found to be better than other techniques including P&O and PSO (Nusaif & Mahmood, 2020; X.-S. Yang, 2008). Experimental results exhibit a better performance regarding tracking efficiency under partial irradiance but have excessive tracking time. A modified FFA for MPPT was introduced, which reduced tracking time and complexity (Chitra, Yogitha, Sivaramakrishnan, Razia Sultana, & Sanjeevikumar, 2020; Teshome, Lee, Lin, & Member, 2016).

3.12. Bat Search Algorithm

The Bat Search Algorithm (BA) is based on the navigation abilities of bats in searching for prey and avoiding obstacles, even in complete darkness (X. S. Yang, 2010). BA was examined for MPPT control design (Oshaba, Ali, & Abd Elazim, 2015). The technique is used for tuning the PI controller parameters to adjust the DC-DC converter duty cycle. The results indicate that the BA-based PI controller is robust and has good performance compared with PSO concerning different parameters. However, this technique requires further investigation, especially for large-scale solar PV plants (Hanzaei, Gorji, & Ektesabi, 2020b)

3.13. Gravitational Search Algorithm

Gravitational Search Algorithm (GSA) functions based on the law of gravity (Rashedi, Nezamabadi-pour, & Saryazdi, 2009). Agents are considered objects, while their performance is measured by their masses. The drawback of GSA is its potentially slow convergence. It is utilized to fine-tune the correction weights of Recurrent Neural Networks (RNN) in a PV system to estimate solar radiation and MPP voltage and shows superior performance in comparison to PSO, Cuckoo, and GWO (Pattnayak, Choudhury, Nayak, Bagarty, & Biswabandhya, 2020; Pervez, Sarwar, Tayyab, & Sarfraz, 2019).

3.14. Fibonacci Search Algorithm

Fibonacci Search Algorithm (FSA) is based on the principle of divide and conquer (Ferguson, 1960) and uses sorted arrays to narrow down potential locations with solutions. The narrowing process utilizes Fibonacci numbers, a series in which every number equals the sum of the preceding two numbers (Ilyas et al., 2020). The initial step consists of examining two voltage values of PV arrays and the output power measured at these values. After applying FSA, the search range shifts to the right or left, and a new power point is obtained. The search continues until MPP is reached (N. A. Ahmed & Miyatake, 2008; Ilyas et al., 2020). An FSA-based MPPT proposed by (N. A. Ahmed & Miyatake, 2008) demonstrates good performance and rapid response for uniform irradiation and PSCs. FSA has been applied for MPPT (Ilyas et al., 2020) and can track the global point in the presence of multiple peaks. FSA with the optimized FLC method is more efficient for pursuing the global power point, as compared to PI controller and FLC technique under PSC.

3.15. Other Metaheuristic Algorithms

Meng and Pan (Meng & Pan, 2016) developed the Monkey King Evolution (MKE) algorithm, where Monkey King will split into several small monkeys to search the solution space and report to the king. Kumar et al. (Kumar, Hussain, Singh, & Panigrahi, 2017a) improved MKE by using a fluctuation coefficient and a mutation operator to reduce the parameter dependency of the MKE algorithm. The improved MKE algorithm called IMKE (Intelligent Monkey King Evolutionary Algorithm) is applied to MPPT to find the GMPP under steady state and PSC (Kumar et al., 2017a). The results indicate that IMKE finds GMPP faster than ABC and PSO. A Random

Forest algorithm incorporating an ensemble learning method for MPPT is found to produce better results than ANN and ANFIS (Shareef, Mutlag, & Mohamed, 2017).

Chaos optimization search is a stochastic search algorithm that uses the technique of chaos theory. Since this algorithm uses random chaotic motion to search the feasible search space, it has excellent global search capabilities for small regions of search space and is different from all evolutionary algorithms. Since single-carrier chaos optimization algorithms have poor search abilities, a two-stage chaos optimization search method is applied for MPPT (Wang, Wei, Zhu, & Zhang, 2014).

Tabu search methods are metaheuristic mathematical optimization methods used for local search of feasible solution space. This algorithm uses a memory structure (Tabu list) that stores the previously visited search space and prohibits the search algorithm from coming back to the previously searched space. A small Tabu search-based MPPT system under PSCs was proposed (Yifei Zheng, Chun Wei, & Shaobo Lin, 2011).

The Harmony Search Algorithm (HS) mimics the improvisation process of a musician's composition technique. In (Kumar, Hussain, Singh, & Panigrahi, 2018), the improved version of HS called Normal Harmony Search (NHS) was applied for MPPT, where the Gaussian distribution factor was applied to enhance the bandwidth of HS. In (Kumar et al., 2018), a reduced sensor scheme not requiring a DC link voltage sensor was proposed. This scheme uses the Power Normalized Kernel Least Mean Square (PNKLMS) algorithm to extract the active component of load power.

Chicken Swarm Optimization (CSO) mimics the hierarchical order and individual foraging behavior, and chickens are separated into several classes. In (Wu, Yu, & Kang, 2018), an enhanced version of CSO was introduced, incorporating a chaotic searching technique to initialize positions and enhance the consistency and ergodicity of the population. The results demonstrate the superior performance of ICSO compared to the low efficiency observed in PSO and BA behaviors. This superiority is attributed to the steady-state stable output and faster convergence speed of ICSO.

The Crow Search Algorithm (CSA) mimics the intelligent skills of the crow in searching for hidden food places. CSA was proposed in (Houam, Terki, & Bouarroudj, 2021) for MPPT under PSCs and compared to PSO and P&O techniques. CSA is found to be more efficient than other techniques in terms of power loss and simplicity.

Aygül et al. (Aygül, Cikan, Demirdelen, & Tumay, 2023) introduced an enhancement to the MPPT procedure by implementing the Butterfly Optimization Algorithm (BOA) alongside existing soft computing techniques like Gray Wolf Optimization (GWO), Particle Swarm Optimization (PSO), and Gravitational Search Algorithm (GSA). The main contribution lies in the improved tracking speed achieved by BOA, offering a promising alternative for real-time applications and demonstrating higher accuracy and better tracking speed compared to other algorithms in recent literature, as verified through simulations in MATLAB/Simulink.

4. HETEROGENEOUS HYBRID TECHNIQUES

Several hybrid techniques for tracking GMPP in a PV system under non-uniform insolation have been developed. The suboptimal convergence of soft computing techniques is overcome by hybrid approaches, which involve combining soft computing with hard computing techniques or using two soft computing techniques that demonstrate optimal convergence and superior performance. In this section, heterogeneous hybrid techniques are discussed. These techniques consist of two or more different methods, with one of them being either metaheuristic or conventional.

4.1. Hybrid GWO-P&O MPPT algorithm

GWO is initially applied offline to bring the operating point near the Maximum Power Point (MPP). Subsequently, Perturb and Observe (P&O) are applied online to enhance convergence during fast-changing irradiance patterns (Mohanty, Subudhi, & Ray, 2017). GWO-P&O ensures faster tracking compared to GWO alone and guarantees the global convergence of the tracking process for a PV system with no oscillations near the Global Maximum Power Point (GMPP). GWO is responsible for controlling the duty ratio of the DC-DC converter to identify the MPP. Once the grey wolves are in proximity, the P&O method, with a small step size, takes over to pinpoint the GMPP. The results demonstrate that the GWO-PO method is adaptable to sudden changes in insolation levels, capable of extracting the maximum power for solar panels under Partial Shading Conditions (PSC), and boasts a short tracking time of 2.7 seconds, outperforming GWO alone.

4.2. Hybrid PSO-PI-based MPPT algorithm

Near the Global Maximum Power Point (GMPP), the velocity of particles in PSO becomes very small, posing a challenge for the algorithm to converge to the GMPP. To enhance convergence speed, the first stage of the hybrid algorithm utilizes PSO to locate the global peak. Once located, the PI-based MPPT controller takes over to improve precision (Kermadi & Berkouk, 2015). An adaptive sampling time strategy is implemented, where each PSO particle represents the reference voltage of the buck-boost converter applied to the controller, and the corresponding power is stored. The input to the PI controller is a variable representing a measure of the change in power to voltage.

4.3. Hybrid SA-P&O method

The main drawback of the SA-based MPPT is its inability to continually track GMPP under PSCs, whereas the P&O is ineffective in finding the GMPP. To overcome the drawbacks of these two methods, the exploration capability of SA is combined with continuous tracking capability near GMPP of the P&O method (Lyden & Haque, 2015a). Results indicate that SA-PO did not converge to GMPP under certain test cases and that there is room for improvement in the continuous tracking of GMPP and optimizing the parameters of the SA.

4.4. Hybrid PSO-P&O method

Sundareswaran et al. (K. Sundareswaran et al., 2015) proposed a hybrid approach that combines the intelligence gathered by PSO with the faster convergence of P&O. The best particle of the PSO when it nears the MPPT is used as an input to the P&O method. The test results indicate that PSO-PO is of high tracking efficiency close to 99%, with a minimum tracking time of 1.2s and a maximum tracking time of 14.3s.

4.5. Hybrid ACO-P&O method

First, the global search capability of ACO is utilized to explore the search space, and after a specific number of ant movements, the traditional P&O method takes over (Kinattingal Sundareswaran et al., 2016). Each ant in ACO-PO represents the duty cycle of the boost converter, and six ants are placed at equal intervals between 10% and 90% of the duty cycle. ACO-PO has been shown to reduce steady-state oscillations and to have high accuracy and fast dynamic convergence. The tracking for different PSCs is 99% efficient and with a very fast convergence compared to the ACO or PSO algorithm.

4.6. Hybrid GSA-P&O Method

The advantages of GSA are combined with those of P&O MPPT under PSCs (K. Sundareswaran, Vigneshkumar, Simon, & Nayak, 2016). After a few iterations, the best agent of GSA, which represents the duty cycle of the converter, is provided as the starting point of the P&O method. GSA-PO is able to track GMPP within 3.11s. When the shading pattern is changed, it is also able to reorient within 3.35 seconds to find the GMPP with no oscillation around the GMPP.

4.7. Hybrid PSO-HC method

This mechanism incorporates the global searching capability of PSO and faster convergence of the HC for MPPT in which only the best particles of PSO are considered by HC (Basiński K, Ufnalski B, 2017). The evaporation rate mechanism accelerates the finding of the new optimal solution during PSC. If the growth of the evaporation rate is active for three iterations, then the re-randomization mechanism is applied. In this mechanism, five consecutive particles are randomly located at specific intervals and all other particles follow the classical PSO rule. The method is found effective.

4.8. Hybrid GA-P&O

Under PSCs, P&O will search for GMPP gradually and may get stuck at LMPP. This drawback is overcome in the proposed GA-P&O hybrid (Daraban et al., 2014; Harrag & Messalti, 2015; Kinattingal Sundareswaran, Palani, & Vigneshkumar, 2015). P&O based on fixed step size suffers from oscillations near GMPP. To overcome this drawback, GA is used to guide the PID controller to produce the step size for the P&O controller that drives the duty cycle of the DC-DC converter (Harrag & Messalti, 2015). The results indicate that the ripple and overshoot are reduced from 0.05% to 0.67%, and 9.67% to 1.3%, respectively.

Six chromosomes representing the duty ratio are uniformly distributed between 10% and 90% of power output in PV characteristics (Kinattingal Sundareswaran et al., 2015). GA performs the first three iterations of GA-PSO and the duty ratio corresponding to the maximum power output is then transferred to the P&O algorithm until it reaches GMPP by dynamically changing the step size. GA-PO can be found near GMPP in the first three iterations with a tracking efficiency of 99.7%. This feature makes GA-PO more efficient than hybrid PSO-PO.

A system-independent GA-PO approach was proposed by (Daraban et al., 2014) in which P&O was embedded into GA for faster convergence towards GMPP, without modifying the sample time. GA-PO can find GMPP.

4.9. Hybrid PSO-INC method

A dormant PSO approach is proposed where particles that sway are put into a dormant state and do not further participate to overcome the slow convergence due to the overlap of search paths of the particles in PSO (Hong et al., 2016; Shi et al., 2015). DPSO algorithm is used until GMPP is reached, followed by INC to track GMPP precisely under PSCs. Even though the steady-state oscillations are reduced in this method, it is suitable only for fixed shading patterns.

4.10. Hybrid P&O-PSO

The important aspect of using PSO for MPPT under PSC lies in the proper initialization of the particles, which will lead to GMPP and faster convergence. A two-stage algorithm was reported in (Lian, Jhang, & Tian, 2014), where P&O is employed to identify the closest local peak, and then, PSO is utilized to find GMPP. The disadvantage of this technique is that it takes a long time to reach GMPP.

4.11. Hybrid Salp swarm optimization and P&O

Salp Swarm Optimization (SSO) mimics the salp behavior, where they gather in a group called salp-chain and the purpose of this is still unknown to researchers. A hybrid SSO-PO algorithm was proposed by (Premkumar, Kumar, Sowmya, & Pradeep, 2021), where the SSO is utilized to find the initial MPP and then, PO follows SSO for faster convergence. The proposed hybrid SSO-PO is compared to stand-alone PO, hybrid whale-optimization algorithm, and hybrid grey-wolf-optimization where high tracking performance is shown by the proposed technique.

4.12 Hybrid Measurement Cell with Perturb and Observe Method

The challenge of reduced solar energy efficiency due to partial shading is addressed by (Morales et al., 2022), proposing a new algorithm that combines Measuring Cell (MC) and Perturb and Observe (P&O) methods to find the Global Maximum Power Point (GMPP). The algorithm efficiently locates the GMPP in two steps, utilizing MC for faster localization and P&O to overcome voltage oscillations, ultimately enhancing performance under irregular radiation conditions. The proposed algorithm is mathematically described, presented in a block diagram, and validated through simulations and experiments.

4.13. Hybrid AI-based MPPT techniques

Khan et al. (Khan et al., 2022) explored and compared various MPPT techniques, including P&O, F-LC, AN-N, and AN-FIS, applied to solar PV, wind, fuel cell, and hybrid renewable energy systems. Simulation results reveal that F-LC MPPT minimizes steady-state oscillations, while two-layer AN-N and AN-FIS MPPTs demonstrate improved response and reduced fluctuations, suggesting the potential of AI-based hybrid MPPT techniques for enhanced efficiency and stability in renewable energy systems.

5. ANALYSIS OF HOMOGENEOUS HYBRID TECHNIQUES

The homogeneous hybrid techniques, which combine two distinct metaheuristic algorithms for GMPPT of PV panels, are analyzed in this section.

5.1. Modified Genetic algorithm and Firefly algorithm

Huang et al. (Huang, Chen, & Ye, 2018) introduced a hybrid modified Genetic Algorithm (GA) and Firefly Algorithm to tackle GA-related challenges such as complex calculations, accuracy reduction with decreasing processing time, and low tracking accuracy under Photovoltaic Solar Cells (PSCs). The selection process of GA and the attraction process of Firefly are integrated to generate a swift response with high accuracy. The hybrid method demonstrated a speed improvement of 69.4% and 42.9%, along with enhanced tracking accuracy by 4.16% and 1.85%, compared to conventional GA and Firefly algorithms, respectively.

5.2. Hybrid Particle Swarm Optimization and Gravitational Search algorithm

A hybrid algorithm is developed that combines the strengths of PSO in global search and the strengths of GSA (Dhas & Deepa, 2013). During every iteration of the hybrid algorithm, the duty cycle of the converter is increased or decreased linearly with respect to the change in PV array power and is found to perform better than conventional PSO and GSA.

5.3. Hybrid Differential Evolution and PSO algorithm

A robust and reliable, system-independent hybrid of Differential Evolution and Particle Swarm Optimization (DEPSO) is applied utilizing a low-cost micro-controller (Mohammadmehdi Seyedmahmoudian et al., 2015). The traditional PSO technique is diversified by using DE operators to avoid local maxima, to explore and exploit the search space smartly, and to accurately locate the GMPP. Each particle in this algorithm represents the terminal voltage of the PV panel and the fitness function is used to maximize the power from the panels. The test results indicate that whenever there is a change in weather or load, the algorithm can recognize the change and find GMPP accurately.

5.4. Hybrid Whale Optimization and Differential Evolution

Inspired by the distinctive hunting mechanism of whales, Mirjalili and Lew developed a Whale Optimization Algorithm (WOA) (Mirjalili & Lewis, 2016). The main drawback of this mechanism is its tendency to stagnate at local optima when the number of search agents is small. Kumar et al.(Kumar, Hussain, Singh, & Panigrahi, 2017b) proposed a hybrid WOA and DE using only four search agents to overcome this issue and to incorporate it in online MPPT. With a small population size, low computational burden, and low steady-state oscillations, this algorithm is ideal for implementation using hardware and is found to be 2 to 5 times faster than other metaheuristic algorithms under different environmental conditions.

5.5. Hybrid Jaya and Differential Evolution

Jaya algorithm works based on the principle of “getting victory by avoiding all failures” (Venkata Rao, 2016). The advantage of the Jaya algorithm is that it is not dependent on specified parameters and moves forward to the best location by avoiding the worst location. The inability of this algorithm to quickly track GMPP is overcome by combining this with DE (Kumar, Hussain, Singh, & Panigrahi, 2017c). Jaya algorithm propels the search agents away from the worst solution, while DE pulls the search agents towards the global solution. It updates the duty cycle during each iteration, passing this information to DE. Utilizing its operators, DE determines the optimal position for all candidates supplied by the Jaya algorithm. With its rapid decision-making ability, a minimal number of three search agents, and a low computational burden for microprocessors, this hybrid method proves to be reliable and easily implementable.

5.6. Hybrid GA and Adaptive PSO

A hybrid GA and adaptive PSO are being developed to improve MPPT control and are found to converge faster to GMPP under PSC and uniform real-time conditions. This approach is beneficial for large PV systems (L. Liu & Liu, 2012).

5.7. Other Hybrid techniques

A modified Queen Bee Genetic Algorithm (MQBGA) is proposed for tuning the scaling factors of FLC (Garud et al., 2021). FLC is used to tune the boost converter duty cycle accurately and match the load at MPP on a real-time basis. This approach facilitates real-time MPP under changeable weather conditions, achieves real-time load matching, and increases the power harnessed from the PV module. Continuous GA (CGA) and Hybrid-PSO (HPSO) are applied for detecting the global power point (Shankar & Mukherjee, 2015). The results obtained using such evolutionary optimization techniques show that HPSO surpasses both the P&O and CGA methods under PSCs. A hybrid approach of PSO and Chaos searching technique (CSTPSO) presented in (Mirebrahimi SM, 2016) improves MPPT and eliminates the drawbacks of standard PSO.

6. RESULTS AND DISCUSSION

The results show that metaheuristic MPPT algorithms are mostly based on conventional P&O, HC, or INC-based techniques as these are simple to implement using low-cost microcontrollers, but are far superior to conventional trackers under PSC or fast-changing environmental conditions. There is a scope for improvement in hardware implementation and real-time application of metaheuristic algorithms to MPPT. However, it is still difficult to identify the most efficient metaheuristic technique for practical implementation.

There is a lack of studies that practically implement Maximum Power Point Tracking (MPPT) for large systems under Perturb and Seek Control (PSC). Most studies utilize random patterns and offline testing to compare their performance with conventional or other techniques. This approach makes it easier to validate the efficiency of the proposed method. However, no standard testing conditions or well-established criteria are currently available to compare the effectiveness of various techniques.

It is essential to note that a fast MPPT may not provide reliable operation under all conditions, and extended tracking time may reduce the efficiency of the system. The challenge in developing metaheuristic algorithms for MPPT lies in selecting the number of particles, the frequency of updating particles, reinitializing particles, and dynamically updating specific parameters of the metaheuristic algorithms.

An ideal metaheuristic algorithm for Global Maximum Power Point Tracking (GMPP) should be system-independent, and tracking accuracy should remain unaffected by the Photovoltaic (PV) array model. It should exhibit low computational complexity, no oscillations near the GMPP, good dynamic performance, and require few parameters to set.

Moreover, different setups, such as PV plant capacity, microcontrollers, and DC-DC converters, are employed for evaluating and tracking power. Therefore, combining these techniques might be unfair, considering that some systems are faster than others. In the literature, no study was found in which all techniques are compared under similar conditions. This study focuses solely on experimental results, and the comparison is limited to techniques studied under nearly similar conditions. This ensures the identification of the most competitive techniques without bias toward any superior setups.

6.1. Comparative analysis of metaheuristic techniques

A comparison of the simulated and experimental results of metaheuristic techniques is made in this subsection. Based on the literature review, the main features and limitations of different metaheuristic techniques are given in Table 2.

Table 2. Comparative analysis of different metaheuristic techniques for MPPT

No.	Technique	Main features	Limitations
1	GA (Dahmane et al., 2013; Dizqah et al., 2014; Hadji et al., 2011; Zagrouba et al., 2010)	Using mutation and crossover gives more variety of the population to search the optimal MPP Accuracy and convergence speed can be balanced by controlling the number of generations Reduces oscillation and power loss as compared to conventional techniques	High complexity Slower than other Metaheuristic techniques The mutation process increases the oscillations due to the big change in new generation values
2	PSO (L. Liu & Liu, 2012),(K. H. Chao, 2015; Miyatake et al., 2011; Sarvi et al., 2015)	Fast response, flexibility, and robustness The memory system helps to converge faster to MPP based on the fitness function Easier to implement than GA The calculation is modest compared to other metaheuristic algorithms	Easily get trapped into a local optimum due to the randomness of initial particles
3	IPSO (Ishaque, Salam, Shamsudin, et al., 2012; H. Li & Liu, 2014; Mirhassani et al., 2015)	Stable output in the steady state under different conditions	More complex than PSO due to adding new hyperparameters
4	ABC (Benyoucef et al., 2015)	Few control parameters as compared to GA and PSO Better performance as compared to PSO and enhanced P&O under PSC	High complexity Slow tracking speed
5	CS (J. Ahmed & Salam, 2014)	Requires few parameters for fine-tuning as compared to PSO and GA Suitable for medium and large-size PV systems Better than P&O and PSO, regarding transient fluctuations, convergence speed, and steady-state performance	High complexity Dependence on the initial points
6	FWA (Sangeetha et al., 2016)	Can balance between exploitation and exploration Good tracking speed Near-zero steady-state oscillations	High complexity High steady-state oscillations
7	SA (Chaves et al., 2016)	One of the most flexible algorithms compared to FWA, GA, PSO, IPSO, CS, and ABC Avoids trapping in local maxima, thus better for PSCs	Requiring a long processing time to obtain high-quality solutions. Requiring random numbers to be generated, which makes hardware implementation difficult due to the complexity
8	GWO (Mohanty et al., 2016)	Demonstrates superior performance, with faster convergence to global peak Faster PV tracking as compared to P&O and improved PSO under PSCs and rapid irradiation changes	High complexity Depends on the initial points. Low response to the rapidly varying conditions.
9	FFA (Chitra et al., 2020; Nusaif & Mahmood, 2020; Teshome et al., 2016; X.-S. Yang, 2008)	Better than P&O and PSO Better performance regarding tracking efficiency and tracking speed under partial irradiance	Excessive tracking time Dependence on the initial points
10	BA (Oshaba, A. S. et al 2015)	BA-based PI controller is robust. Good performance concerning changes in load torque, radiation, and temperature as compared to PSO	Low efficiency Requiring more studies to confirm its behavior
11	GSA (Pattnayak et al., 2020; Pervez et al., 2019)	- Superior performance in comparison to PSO, CS, and GWO	Potentially slow convergence
12	FSA (N. A. Ahmed & Miyatake, 2008; Ilyas et al., 2020)	Good performance and rapid response under uniform irradiation and PSCs FSA with optimized FLC method is more efficient for GMPPT under PSC, as compared to the PI controller and FLC techniques	Less efficient than other methods Low tracking speed Failure to track GMPP in some cases.
13	ACO (Lian Lian Jiang et al., 2013)	Applicable to problems with dynamic changes, as it runs without interruption during real-time changes Better performance than P&O and PSO	High complexity due to using more parameters. Low response to the rapid varying in conditions.

The simulation results of some metaheuristic techniques are found to be close to experimental results, as shown in Table 3. However, it is hard to identify the best technique because each method is evaluated using different scenarios and is compared with specific techniques. However, other algorithms should be tested and validated experimentally.

Table 3. Comparative analysis of simulation and experimental results for different metaheuristic techniques

No.	Reference	Technique	Simulation results	Experimental results
1	Ishaque K et. al. (Ishaque, Salam, Amjad, et al., 2012)	IPSO is compared with the HC technique. Three scenarios are used to test the system: i. large step change in (uniform) solar insolation ii. step-change in load iii. PSCs	Results show a steady state without oscillations using the proposed technique as compared to 9W loss out of 240W when using HC. IPSO outperforms the HC in GMPPT in all test cases. About 11% loss in power is detected by using HC in the case of PSCs. IPSO is faster in tracking the sudden changes in the environment, which means that less power would be lost. 50% of the load is applied and IPSO is found to respond faster to the load changing so that less power will be lost.	Experimental results are based on using a custom-designed PV array simulator (PVAS2). There are no steady-state oscillations. IPSO performs better than the HC in finding the GMPP in all test cases. IPSO is faster in tracking the sudden changes in the load on the environment. 50% of load changing is applied; IPSO is found to respond faster than the HC to the load changing. High-speed tracking causes less power loss
2	Mohanty S et. al. (Mohanty et al., 2016)	GWO is compared with IPSO and P&O under partial shading conditions. Two cases are discussed: with 2 and 4 MPP peaks.	Simulation shows that GWO and IPSO are found to converge to the MPP, but the P&O technique gives poor MPP results. GWO gives slightly better output power (about 0-1 W) and significant improvement in the tracking time as compared to IPSO. However, time is not mentioned. GWO also reaches the steady state faster than IPSO and P&O.	Experimentally GWO and IPSO are found to converge to the same MPP, but the P&O technique gives poor MPP results. The tracking speed of GWO is found faster than IPSO as it takes 3.18s to reach MPP, whereas IPSO takes 7.9s to reach MPP. The converging speed of GWO is also faster than IPSO. GWO reaches a steady state faster than IPSO.
3	Ahmed N.A et. al. (N. A. Ahmed, Abdul Rahman, & Alajmi, 2021)	GA and CS are presented to tune the PID and FOPID controllers.	Best performance is obtained using GA with ISE cost function for PID controllers and CS with IAE cost function for FOPID. The overall efficiency of the GA tuning algorithm using ISE for PID controllers is 99.73% which is almost 1.28% superior to the overall efficiency of the manual tuning approach. The overall efficiency of the CS tuning algorithm using IAE for FOPID controllers is 99.72% which is almost 1.27% superior to the overall efficiency of the manual tuning approach.	PID-based GA is compared to a manually adjusted controller. PID-based GA is found to reach the MPP faster than the manually adjusted controller. Steady-state oscillation is lower when using PID-based GA.

Table 3 shows that due to the validation of simulation results and by comparing the algorithms used in different studies, the GWO algorithm is found to be the most competitive algorithm among the stand-alone metaheuristic algorithms due to its behavior as it shows high efficiency, fast speed convergence, and stable steady state.

6.2. Comparative analysis of heterogeneous hybrid techniques

The performance metrics of different heterogeneous hybrid techniques are compared in Table 4. In each study, different PV system configurations (modules connected in series (s) and/or parallel (p)) are used for software testing. The hardware implementation also varies between these studies as each study uses a different controller for different systems.

However, other algorithms are also required to be tested and validated experimentally, to be able to define precisely which technique is the best. Due to the available experiments and results, as shown in Table 5, the GWO-PO algorithm is found to be the most competitive algorithm as compared to other algorithms in other studies in terms of convergence time and efficiency achieved by each method.

Table 4. Comparative analysis of heterogeneous hybrid techniques

Methods / Parameters	GWO-P&O (Mohanty et al., 2017)	PSO-PI (Kermadi & Berkouk, 2015)	SA-P&O (Lyden & Haque, 2015a)	PSO-P&O (K. Sundareswaran et al., 2015)	ACO-P&O (Kinattingal Sundareswaran et al., 2016)	GSA-P&O (K. Sundareswaran et al., 2016)	PSO-HC (Basińs ki K, Ufnals ki B, 2017)	GA-P&O (Kinattingal Sundareswaran et al., 2015)	GA-P&O (Daraban et al., 2014)	GA-P&O (Harrag & Messaoudi, 2015)	PSO-INC (Shi et al., 2015)
Implementation Complexity	Medium	Medium	Medium	High	low	High	Low	Medium	High	High	High
Convergence Speed	Moderate	Fast	Slow	Moderate	Moderate	Moderate	NA	Moderate	Fast	Fast	Fast
GMPP tracking capability	Accurate	Reliable	Reliable	Accurate	Accurate	Reliable	Reliable	Accurate	Accurate	Accurate	Accurate
Oscillations Around MPP	No	Yes	Not Tested	Yes	Yes	No	Yes	No	No	No	No
System configurations used for Software Testing (no. of PV panels in series (s) &parallel (p))	3-s& 3-s2-p	4-s4-p	Not provided	6s& 3s2p	5s& 2s4p	3s& 5s2p	3s	4s2p& 3s2p	Not used	Not used	3s
Hardware testing	Done	Not Done	Not Done	Not done	Done	Done	Not Done	Done	Done	Not Done	Done
Microcontroller/ software and Converter	dSPACE Boost	-	-	-	PIC Boost	PIC Boost	-	PIC Boost	TMS320F2808 Buck	-	Boost

Table 5. Comparison of simulation and experimental results for different heterogeneous hybrid techniques under PSCs

No.	Reference	Technique	Simulation Results	Experimental results
1	Shi J et al. (Shi et al., 2015)	Hybrid dormant PSO with INC is presented DPSO-INC is compared with CPSO-INC and conventional INC	DPSO-INC is found to be faster in tracking GMPP, whereas CPSO-INC needs a longer time and is in some cases not able to track GMPP INC cannot track GMPP	The same observations are found in the experimental work
2	Mohanty S et al. (Mohanty et al., 2017)	Hybrid GWO-P&O MPPT algorithm is presented GWO-PO is compared to GWO and PSO-PO	The efficiency of GWO-P&O for different patterns of insolation is found to be between 99.84 and 100%, while the individual GWO or PSO-PO techniques are less efficient Tracking time is found to be two or three times less (between 0.007s and 0.015s) than the other techniques No steady-state oscillations	GWO-P&O can converge within 2.7s; however, GWO and PSO-PO take 3.1s and 3.2s, respectively Under rapidly changing insolation, GWO-P&O is able to converge within 2.4s; however, GWO and PSO-PO take 3.8s and 4s respectively
3	Sundareswaran K et al (K. Sundareswaran et al., 2016)	GSA-P&O algorithm is presented GSA-PO is compared to the original GSA algorithm and P&O technique	GSA-PO can reach the MPP faster than the original GSA (about 4s as compared to 15s) while it still gives similar efficiency	GSA-PO achieves around 99.9% efficiency which is the same as GSA but better than PO GSA-PO is faster (3.2s) than the original GSA around (13.0s) GSA-PO was found to be more efficient
4	Sundareswaran K et al. (Kinattingal Sundareswaran et al., 2015)	GA-PO technique is presented GA-PO algorithm is compared to the original GA algorithm and the PSO-PO	GA does not guarantee convergence to GMPP consistently GA-PO achieves a slight improvement in the tracking speed than PSO-PO and it guarantees convergence to GMPP	PSO-PO could be stuck in the local maxima, but the GA-PO will always converge to the global maxima GA-PO efficiency is found to be between 99.75% and 99.95% with 3.8s to 5.9s tracking time, which is slightly better than PSO-PO
5	Lian KL et al. (Lian et al., 2014)	Hybrid PSO with P&O algorithm is presented PSO-PO is compared to the original PSO algorithm	No simulation is done	Both PSO and PSO-PO are found to be able to converge to the GMPP; however, the PSO-PO is faster than PSO (more than 10s in some cases)

6.3. Comparative analysis of homogeneous hybrid techniques

A comparison of the simulated and experimental results of homogeneous hybrid techniques is presented in this section. A comparison of algorithms that have been experimentally validated is shown in Table 6.

Table 6. Comparison of simulation and experimental results for different homogeneous hybrid techniques under partial shading conditions

No.	Reference	Technique	Simulation Results	Experimental Results
1	Seyed Mahmoudian M et al. (Mohammadmehdi Seyedmahmoudian et al., 2015)	DE is integrated with PSO	DEPSO can reach the GMPP in all case studies	The efficiency of DEPSO varies between 97.5% and 98.2%
2	Huang Y-P et al. (Huang et al., 2018)	GA is integrated with FA improved via DE GA-FA is compared with the original GA and FA	GA and FA are found to be slower and less efficient than integrated GA-FA algorithms where they could stack in an LMPP in some cases The average tracking times of GA and FA are 0.114s and 0.111s as compared to only 0.036s for GA-FA Average errors of GA and FA are 7.72% and 7.05% compared to only 0.74% for GA-FA	The average tracking times of GA and FA are 0.291s and 0.156s as compared to only 0.089s for GA-FA Average errors of GA and FA are 6.9% and 4.59% as compared to only 2.74% for GA-FA
3	Kumar N et al. (Kumar et al., 2017b)	WO is integrated with DE WODE is compared with the original GWO and IPSO	The efficiency of WODE varies between 98% and 99% as compared to (85 to 89%) for IPSO and (94 to 95%) for GWO WODE tracking time varies between 1.2-1.4s as compared to 7.5-8.2s for IPSO and 3-4.1s for GWO	The efficiency of WODE is around 98% as compared to 87% for IPSO and 95% for GWO WODE tracking time varies between 1.4-1.5s as compared to 7.5-8.3s for IPSO and 3.1-4.3s for GWO
4	Kumar N et al. (Kumar et al., 2017c)	Hybrid 'Jaya' and DE algorithm is presented JayaDE is compared to FPA, PSO, and hybrid ACO-PO	JayaDE's MPPT average tracking time is 0.48s as compared to 0.77s for FPA, 5.59s for PSO, and 3.12s for ACO-PO	JayaDE's average tracking time is 0.52s as compared to 0.83s for FPA and 3.42s for ACOPO

Table 4 shows that each technique is tested using different conditions and most of these studies are not validated experimentally; however, all these techniques exhibit good performance for MPPT. The simulation and experimental results of some heterogeneous hybrid techniques are analyzed in Table 5.

Indeed, GA-FA and JayaDE used different setups, making it difficult to compare them in terms of system superiority achieved by using advanced controllers or other advanced devices. As shown in Table 6, the GA-FA algorithm provides less tracking time, but it is not compared with other hybrid techniques. On the other hand, JayaDE is compared with two different metaheuristic techniques (FPA and PSO), in addition to one hybrid technique (ACO-PO), and it achieves higher efficiency than all of them with less tracking time and higher accuracy. Therefore, it can be concluded that JayaDE is the most competitive technique for MPPT among homogeneous hybrid techniques. However, it's worth noting that some of the hybrid techniques mentioned are not experimentally validated. This study identifies GWO as the most competitive technique among standalone metaheuristic techniques, GWO-PO among heterogeneous hybrid techniques, and JayaDE among homogeneous hybrid techniques. All three identified techniques have been experimentally validated, demonstrating zero steady-state oscillations. They exhibit the capability to reach the GMPP quickly and maintain very good efficiency under varying loads, irradiance, temperature, and other climatic conditions.

7. CONCLUSIONS AND FUTURE RESEARCH AREAS

In this study, advanced metaheuristic and hybrid homogeneous and heterogenous metaheuristic techniques for MPPT were analyzed to improve the performance of photovoltaic systems for power generation under varying solar irradiance (partial/complete shading), temperature, and load. Based on the study's findings, the following conclusions can be drawn:

1. To quantify the performance of MPPT accurately, a standard testing procedure and evaluation criteria for comparing the metaheuristic algorithms and their variants must be established instead of selecting the parameters by trial and error. An analysis of each system parameter on the system performance must be carried out. Such studies are planned in the follow-up research.
2. Most of the researchers have not followed standard metrics to evaluate different MPPT algorithms; this study identifies the most competitive techniques based on the experimental studies for three classes of advanced metaheuristic algorithms where extensive evaluation and comparison were done under nearly similar conditions.
3. Based on the experimental results, GWO, GWO-PO, and JayaDE are found to be the most competitive techniques among the advanced metaheuristic techniques and are found to achieve a superior performance under all conditions to find GMPP faster with zero steady-state oscillations and very good efficiency.
4. The advanced metaheuristic techniques are found to be superior to the conventional techniques in finding the GMPP, thus improving the optimum power generation by

a PV system under complete/partial shading or fast-changing irradiance and other environmental conditions.

5. The ability of metaheuristic algorithms to be implemented using low-cost and simple controllers makes this field promising, which indicates that there is further scope for hardware improvement of metaheuristic algorithms implementation in photovoltaic power systems.
6. It is important to apply the metaheuristic techniques and test them under different climatic conditions for different PV technologies for the appropriate selection of an MPPT control technique and to study their effectiveness under actual outdoor conditions in different locations worldwide. Such studies are planned as follow-up research on actual solar PV plants.

The study provides a clear understanding of the state-of-the-art PV MPPT techniques, under actual varying climatic and partial shading conditions, which will be a valuable tool for researchers and the solar PV industry with the intention to improve the performance of existing and future solar power plants worldwide (Chandel S.S. et al.2023, Chandel R., et al.2022).

7.1. Identified Future Research Areas

In future studies, a standard testing procedure and evaluation criteria for comparing metaheuristic algorithms and their variants can be established. Instead of selecting parameters for metaheuristic algorithms through trial and error, it is essential to conduct an analysis of each system parameter's impact on system performance. Dynamic adjustment of parameters and optimal parameter settings under PSCs must be considered. Rather than relying on ideal assumptions to simulate environmental conditions, the testing of the system should be conducted under real weather conditions. During sensor faults, it is crucial to investigate the convergence of the metaheuristic algorithm. Advanced algorithms can be employed to study large-scale power plants with possible integration into existing PV simulation software. There are opportunities for developing new hybrid metaheuristic methods, for enhanced efficiency of PV modules and load forecasting and in other areas of optimization to combine the best features of the individual algorithms to improve the tracking time and accuracy. These will be taken up in the follow-up research.

Exploring future avenues in the field of Maximum Power Point Tracking (MPPT) techniques for enhanced solar photovoltaic (PV) power generation is crucial. Based on insights gained from comparing various MPPT techniques under partial shading conditions, it is evident that their effectiveness is closely tied to diverse factors. As we look toward future investigations, it becomes paramount to consider potential variations in conditions beyond irradiation, such as converter topologies, wind direction, and temperature. The integration of a coefficient for comparison emerges as a promising approach to standardize results, facilitating a more precise comparative analysis. This coefficient, designed to account for the influence of diverse environmental factors and system configurations, holds the potential to establish a fair evaluation framework across different scenarios. A collective effort to define standard conditions or reference scenarios would contribute to the development of a universally applicable comparison framework, fostering a comprehensive understanding of how MPPT techniques respond to varying real-world conditions and optimizing their implementation in practical PV systems. This future research direction aims to enhance the reliability and applicability of MPPT techniques across diverse contexts (Chandel and Chandel 2022).

NOMENCLATURE

ABC	Artificial Bee Colony	MPP	Maximum Power Point
ACO	Ant Colony Optimization	MPPT	Maximum Power Point Tracking
ANN	Artificial Neural Network	MAPE	Mean Absolute Percent Error
BA	Bat Search Algorithm	MARE	Mean Absolute Relative Error
CS	Cuckoo Search	MBE	Mean Bias Error
DC	Direct Current	MBE	Mean Bias Error
FSA	Fibonacci Search Algorithm	MLP	Multi-Layer Perceptron
FFA	Firefly Algorithm	MLP	Multi-Layer Perceptron
FWA	Firework Algorithm	nRMSE	Normalized Root Mean Square Error
FOPID	Fractional Order PID	PSC	Partial Shaded Conditions
FLC	Fuzzy Logic Controller	PSC	Partial Shading Conditions
GA	Genetic Algorithm	PSO	Particle Swarm Optimization
GA	Genetic Algorithm	P&O	Perturbation And Observation
GMPP	Global Maximum Power Point	PV	Photovoltaic
GSA	Gravitational Search Algorithm	PPT	Power Point Tracking
GWO	Grey Wolf Optimization	PI	Proportional Integral
HC	Hill Climbing	PID	Proportional Integral Derivative
IPSO	Improved PSO	RMSE	Root Mean Square Error
IC	Incremental Conductance	SA	Simulating Annealing
LMPP	Local Maximum Power Point		

Authors Declaration of interests

☒ 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 Statement

The data used will be provided on request.

REFERENCES

1. Abdulaziz, S., Attlam, G., Zaki, G., & Nabil, E. (2022). Cuckoo search algorithm and particle swarm optimization based maximum power point tracking techniques. *Indonesian Journal of Electrical Engineering and Computer Science*, 26(2), 605–616. Retrieved 20 December 2023 from https://doi.org/10.11591/IJEECS.V26.I2.PP605-616
2. Abu Eldahab, Y. E., Saad, N. H., & Zekry, A. (2014). Enhancing the maximum power point tracking techniques for photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 40, 505–514. https://doi.org/10.1016/J.RSER.2014.07.202
3. Aguila-Leon, J., Vargas-Salgado, C., Chiñas-Palacios, C., & Díaz-Bello, D. (2023). Solar photovoltaic Maximum Power Point Tracking controller optimization using Grey Wolf Optimizer: A performance comparison between bio-inspired and traditional algorithms. *Expert Systems with Applications*, 211, 118700. Retrieved 20 December 2023 from https://doi.org/10.1016/J.ESWA.2022.118700
4. Ahmed, J., & Salam, Z. (2014). A Maximum Power Point Tracking (MPPT) for PV system using Cuckoo Search with partial shading

capability. *Applied Energy*, 119, 118–130. https://doi.org/10.1016/j.apenergy.2013.12.062

5. Ahmed, N. A., & Miyatake, M. (2008). A novel maximum power point tracking for photovoltaic applications under partially shaded insolation conditions. *Electric Power Systems Research*, 78(5), 777–784. https://doi.org/10.1016/J.EPSR.2007.05.026
6. Ahmed, N. A., Abdul Rahman, S., & Alajmi, B. N. (2021). Optimal controller tuning for P&O maximum power point tracking of PV systems using genetic and cuckoo search algorithms. *International Transactions on Electrical Energy Systems*, 31(10), 1–21. https://doi.org/10.1002/2050-7038.12624
7. Ahmed, S., Mekhilef, S., Mubin, M. B., & Tey, K. S. (2022). Performances of the adaptive conventional maximum power point tracking algorithms for solar photovoltaic system. *Sustainable Energy Technologies and Assessments*, 53, 102390. Retrieved 20 December 2023 from https://doi.org/10.1016/J.SETA.2022.102390
8. Al Garni, H. Z., & Awasthi, A. (2017). Solar PV power plant site selection using a GIS-AHP based approach with application in Saudi Arabia. *Applied Energy*, 206C, 1225–1240. https://doi.org/10.1016/j.apenergy.2017.10.024
9. Al Garni, H. Z., Awasthi, A., & Ramli, M. A. M. (2018). Optimal design and analysis of grid-connected photovoltaic under different tracking systems using HOMER. *Energy Conversion and Management*, 155C, 42–57.
https://www.researchgate.net/publication/370761188_Optimal_Design_and_Analysis_of_Grid-Connected_Solar_Photovoltaic_Systems
10. Al Garni, H. Z., Awasthi, A., & Wright, D. (2019). Optimal orientation angles for maximizing energy yield for solar PV in Saudi Arabia. *Renewable Energy*, 133, 538–550. https://doi.org/10.1016/j.renene.2018.10.048
11. Ali, A., Almutairi, K., Malik, M. Z., Irshad, K., Tirth, V., Algarni, S., … Shukla, N. K. (2020). Review of online and soft computing maximum power point tracking techniques under non-uniform solar irradiation conditions. *Energies*, 13(12). https://doi.org/10.3390/en13123256
12. Amine, H. M., Abdelaziz, H., & Najib, E. (2015). Maximum Power Point Tracking Using IT2FL Tuned with GA. *Energy Procedia*, 83, 399–407. https://doi.org/10.1016/J.EGYPRO.2015.12.215
13. Aygül, K., Cikan, M., Demirdelen, T., & Tumay, M. (2023). Butterfly optimization algorithm based maximum power point tracking of photovoltaic systems under partial shading condition. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 45(3), 8337–8355. Retrieved 20 December 2023 from https://doi.org/10.1080/15567036.2019.1677818
14. Baños, R., Manzano-Agugliaro, F., Montoya, F. G., Gil, C., Alcayde, A., & Gómez, J. (2011). Optimization methods applied to renewable and sustainable energy: A review. *Renewable and Sustainable Energy Reviews*, 15(4), 1753–1766. https://doi.org/10.1016/J.RSER.2010.12.008
15. Basiński K, Ufnalski B, G. L. M. (2017). Hybrid MPPT algorithm for PV systems under partially shaded conditions using a stochastic evolutionary search and a deterministic hill climbing. *Power Electronics and Drives*, 2(2), 49–59. https://doi.org/10.5277/PED170212
16. Başoğlu, M. E. (2022). Comprehensive review on distributed maximum power point tracking: Submodule level and module level MPPT strategies. *Solar Energy*, 241, 85–108. Retrieved 20 December 2023 from https://doi.org/10.1016/J.SOLENER.2022.05.039
17. Beheshti, Z., Mariyam, S., & Shamsuddin, H. (2013). *A Review of Population-based Meta-Heuristic Algorithm*. *Int. J. Advance. Soft Comput. Appl* (Vol. 5) https://www.researchgate.net/publication/270750820_A_review_of_population-based_meta-heuristic_algorithm
18. Belhachat, F., & Larbes, C. (2018). A review of global maximum power point tracking techniques of photovoltaic system under partial shading conditions. *Renewable and Sustainable Energy Reviews*, 92(January), 513–553. https://doi.org/10.1016/j.rser.2018.04.094
19. Belhachat, F., & Larbes, C. (2019). Comprehensive review on global maximum power point tracking techniques for PV systems subjected to partial shading conditions. *Solar Energy*, 183(October 2018), 476–500. https://doi.org/10.1016/j.solener.2019.03.045
20. Bellala DJ, C. M. (2007). Genetic algorithm technique for optimizing the maximum supplied power of a photovoltaic module under various atmospheric conditions. *Journal of Electrical Engineering*, 7(4), 309–332. http://mail.jee.ro/index.php/jee/article/view/WN1181147660W4666e20cb76e4
21. Bendib, B., Belmili, H., & Krim, F. (2015). A survey of the most used MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 45, 637–648. https://doi.org/10.1016/J.RSER.2015.02.009
22. Benyoucef, A. soufyane, Chouder, A., Kara, K., Silvestre, S., & sahed, O. A. (2015). Artificial bee colony based algorithm for maximum power point tracking (MPPT) for PV systems operating under partial shaded conditions. *Applied Soft Computing*, 32, 38–48. https://doi.org/10.1016/J.ASOC.2015.03.047
23. Chandel, R., Chandel, S.S, Prasad, D., Dwivedi R.P (2022), Review on thermoelectric systems for enhancing photovoltaic power generation, Sustainable Energy Technologies and Assessments, https://doi.org/10.1016/j.seta.2022.102585
24. Chandel, R., Chandel, S.S. (2022) Performance analysis outcome of a 19-MWp commercial solar photovoltaic plant with fixed-tilt, adjustable-tilt, and solar tracking configurations. Prog Photovoltaics Res Appl. 30(1):27–48. https://doi.org/10.1002/PIP.3458
25. Chandel, S.S, Gupta, A., Chandel R., Tajjour, S. (2023), Review of deep learning techniques for power generation prediction of industrial solar photovoltaic plants, Solar Compass 8, 100061, https://doi.org/10.1016/j.solcom.2023.100061
26. Chao, K. H. (2015). A high performance PSO-based global MPP tracker for a PV power generation system. *Energies*, 8(7), 6841–6858. https://doi.org/10.3390/en8076841
27. Chao, R.-M., Nasirudin, A., Wang, I.-K., & Chen, P.-L. (2016). Multicore PSO Operation for Maximum Power Point Tracking of a Distributed Photovoltaic System under Partially Shading Condition. *International Journal of Photoenergy*, 2016, 1–19. https://doi.org/10.1155/2016/9754514
28. Chaves, E. N., Reis, J. H., Coelho, E. A. A., Freitas, L. C. G., Júnior, J. B. V, & Freitas, L. C. (2016). Simulated Annealing – MPPT in Partially Shaded PV Systems. *Ieee Latin America Transactions*, 14(1), 235–241. https://doi.org/10.1109/TLA.2016.7430084
29. Chitra, A., Yogitha, G., Sivaramakrishnan, K., Razia Sultana, W., & Sanjeevikumar, P. (2020). Modified Firefly-Based Maximum Power Point Tracking Algorithm for PV Systems Under Partial Shading Conditions. *Artificial Intelligent Techniques for Electric and Hybrid Electric Vehicles*, 143–163. https://doi.org/10.1002/9781119682035.ch8
30. Chowdhury, S. R., Mukherjee, D., & Saha, H. (2009). FPGA based maximum power point tracker of partially shaded solar photovoltaic arrays using modified adaptive perceptive particle swarm optimization. *International Journal on Smart Sensing and Intelligent Systems*, 2(4), 661–675. https://doi.org/10.21307/ijssis-2017-374
31. Dahmane, M., Bosche, J., El-Hajjaji, A., & Pierre, X. (2013). MPPT for photovoltaic conversion systems using genetic algorithm and robust control. In *2013 American Control Conference* (pp. 6595–6600). IEEE. https://doi.org/10.1109/ACC.2013.6580874
32. Daraban, S., Petreus, D., & Morel, C. (2014). A novel MPPT (maximum power point tracking) algorithm based on a modified genetic algorithm specialized on tracking the global maximum power point in photovoltaic systems affected by partial shading. *Energy*, 74(C), 374–388. https://doi.org/10.1016/j.energy.2014.07.001
33. Dhas, B. G. S., & Deepa, S. N. (2013). A hybrid PSO and GSA-based maximum power point tracking algorithm for PV systems. In *2013 IEEE International Conference on Computational Intelligence and Computing Research* (pp. 1–4). IEEE. https://doi.org/10.1109/ICCIC.2013.6724181
34. Dizqah, A. M., Maheri, A., & Busawon, K. (2014). An accurate method for the PV model identification based on a genetic algorithm and the interior-point method. *Renewable Energy*, 72, 212–222. https://doi.org/10.1016/J.RENENE.2014.07.014
35. Dorigo, Marco., & Stützle, Thomas. (2004). *Ant colony optimization*. MIT Press. https://mitpress.mit.edu/9780262042192/ant-colony-optimization/
36. Eberhart, R., & Kennedy, J. (n.d.). A new optimizer using particle swarm theory. In *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science* (pp. 39–43). IEEE. https://doi.org/10.1109/MHS.1995.494215
37. El-Arini, M. M. M., Othman, A. M., & Fathy, A. (2013). A New Optimization Approach for Maximizing the Photovoltaic Panel Power Based on Genetic Algorithm and Lagrange Multiplier Algorithm. *International Journal of Photoenergy*, 2013, 1–12. https://doi.org/10.1155/2013/481468

38. Eltawil, M. A., & Zhao, Z. (2013). MPPT techniques for photovoltaic applications. *Renewable and Sustainable Energy Reviews*, 25, 793–813. https://doi.org/10.1016/j.rser.2013.05.022

39. Emile Aarts, J. K. and W. M. (2014). Simulated Annealing. In *Search Methodologies: Introductory Tutorials in Optimization and Decision Support Techniques, Second Edition* (pp. 265–284). New York: pringer Science+Business Media. https://doi.org/10.1007/978-1-4614-6940-7

40. Farh, H. M. H., Eltamaly, A. M., & Othman, M. F. (2018). Hybrid PSO-FLC for dynamic global peak extraction of the partially shaded photovoltaic system. *PLOS ONE*, 13(11), e0206171. https://doi.org/10.1371/journal.pone.0206171

41. Ferguson, D. E. (1960). Fibonaccian searching. *Communications of the ACM*, 3(12), 648. https://doi.org/10.1145/367487.367496

42. Gandomi, A. H., Yang, X. S., & Alavi, A. H. (2013). Cuckoo search algorithm: A metaheuristic approach to solve structural optimization problems. *Engineering with Computers*, 29(1), 17–35. https://doi.org/10.1007/s00366-011-0241-y

43. Garud, K. S., Jayaraj, S., & Lee, M. Y. (2021). A review on modeling of solar photovoltaic systems using artificial neural networks, fuzzy logic, genetic algorithm and hybrid models. *International Journal of Energy Research*, 45(1), 6–35. https://doi.org/10.1002/er.5608

44. Gokilapriya, D., & Barvin Banu, S. (2015). MPPT Measurement of Photovoltaic System Under Partial Shading Condition Using DPSO Algorithm (pp. 1037–1046). Springer, New Delhi. https://doi.org/10.1007/978-81-322-2119-7_101

45. Gupta, A., Chauhan, Y. K., & Pachauri, R. K. (2016). A comparative investigation of maximum power point tracking methods for solar PV system. *Solar Energy*, 136, 236–253. https://doi.org/10.1016/J.SOLENER.2016.07.001

46. Hadjaissa, A., Ait cheikh, S. M., Ameur, K., & Essounbouli, N. (2016). A GA-based optimization of a fuzzy-based MPPT controller for a photovoltaic pumping system, Case study for Laghouat, Algeria. *IFAC-PapersOnLine*, 49(12), 692–697. https://doi.org/10.1016/J.IFACOL.2016.07.791

47. Hadji, S., Krim, F., & Gaubert, J. P. (2011). Development of an algorithm of maximum power point tracking for photovoltaic systems using genetic algorithms. In *7th International Workshop on Systems, Signal Processing and their Applications, WoSSPA 2011* (pp. 43–46). IEEE. https://doi.org/10.1109/WOSSPA.2011.5931408

48. Hanzaei, S. H., Gorji, S. A., & Ektesabi, M. (2020a). A scheme-based review of MPPT techniques with respect to input variables including solar irradiance and PV arrays' temperature. *IEEE Access*, 8, 182229–182239. https://doi.org/10.1109/ACCESS.2020.3028580

49. Hanzaei, S. H., Gorji, S. A., & Ektesabi, M. (2020b). A scheme-based review of MPPT techniques with respect to input variables including solar irradiance and PV arrays' temperature. *IEEE Access*, 8, 182229–182239. https://doi.org/10.1109/ACCESS.2020.3028580

50. Harrag, A., & Messalti, S. (2015). Variable step size modified P&O MPPT algorithm using GA-based hybrid offline/online PID controller. *Renewable and Sustainable Energy Reviews*, 49, 1247–1260. https://doi.org/10.1016/J.RSER.2015.05.003

51. Hayder, W., Ogliari, E., Dolara, A., Abid, A., Hamed, M. Ben, & Sbita, L. (2020). Improved PSO: A comparative study in MPPT algorithm for PV system control under partial shading conditions. *Energies*, 13(8). https://doi.org/10.3390/en13082035

52. Hong, Y.-Y., Beltran, A. A., & Paglinawan, A. C. (2016). A Chaos-Enhanced Particle Swarm Optimization with Adaptive Parameters and Its Application in Maximum Power Point Tracking. *Mathematical Problems in Engineering*, 2016, 1–19. https://doi.org/10.1155/2016/6519678

53. Houam, Y., Terki, A., & Bouarroudj, N. (2021). An Efficient Metaheuristic Technique to Control the Maximum Power Point of a Partially Shaded Photovoltaic System Using Crow Search Algorithm (CSA). *Journal of Electrical Engineering and Technology*, 16(1), 381–402. https://doi.org/10.1007/s42835-020-00590-8

54. Huang, Y.-P., Chen, X., & Ye, C.-E. (2018). Research Article A Hybrid Maximum Power Point Tracking Approach for Photovoltaic Systems under Partial Shading Conditions Using a Modified Genetic Algorithm and the Firefly Algorithm. *International Journal of Photoenergy*, 2018, 1–13. https://doi.org/10.1155/2018/7598653

55. Ilyas, A., Ayyub, M., & Khan, M. R. (2020). Modelling and simulation of MPPT techniques for solar photovoltaic system using genetic algorithm optimised fuzzy logic controller. *International Journal of Energy Technology and Policy*, 16(2), 174–195. https://doi.org/10.1504/IJETP.2020.105507

56. Ishaque, K., & Salam, Z. (2013). A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. *IEEE Transactions on Industrial Electronics*, 60(8), 3195–3206. https://doi.org/10.1109/TIE.2012.2200223

57. Ishaque, K., Salam, Z., Amjad, M., & Mekhilef, S. (2012). An improved particle swarm optimization (PSO)-based MPPT for PV with reduced steady-state oscillation. *IEEE Transactions on Power Electronics*, 27(8), 3627–3638. https://doi.org/10.1109/TPEL.2012.2185713

58. Ishaque, K., Salam, Z., Shamsudin, A., & Amjad, M. (2012). A direct control based maximum power point tracking method for photovoltaic system under partial shading conditions using particle swarm optimization algorithm. *Applied Energy*, 99, 414–422. https://doi.org/10.1016/j.apenergy.2012.05.026

59. Jiang, Lian L., Srivatsan, R., & Maskell, D. L. (2018). Computational intelligence techniques for maximum power point tracking in PV systems: A review. *Renewable and Sustainable Energy Reviews*, 85, 14–45. https://doi.org/10.1016/J.RSER.2018.01.006

60. Jiang, Lian Lian, Maskell, D. L., & Patra, J. C. (2013). A novel ant colony optimization-based maximum power point tracking for photovoltaic systems under partially shaded conditions. *Energy and Buildings*, 58, 227–236. https://doi.org/10.1016/J.ENBUILD.2012.12.001

61. Jordehi, A. R. (2016). Maximum power point tracking in photovoltaic (PV) systems: A review of different approaches. *Renewable and Sustainable Energy Reviews*, 65, 1127–1138. https://doi.org/10.1016/J.RSER.2016.07.053

62. KARABOGA, D. (2005). *An idea based on honey bee swarm for numerical optimization*. https://abc.erciyes.edu.tr/pub/tr06_2005.pdf

63. Karaboga, D., & Akay, B. (2009). A comparative study of Artificial Bee Colony algorithm. *Applied Mathematics and Computation*, 214(1), 108–132. https://doi.org/10.1016/j.amc.2009.03.090

64. Katche, M. L., Makokha, A. B., Zachary, S. O., & Adaramola, M. S. (2023). A Comprehensive Review of Maximum Power Point Tracking (MPPT) Techniques Used in Solar PV Systems. *Energies 2023, Vol. 16, Page 2206*, 16(5), 2206. Retrieved 20 December 2023 from https://doi.org/10.3390/EN16052206

65. Kermadi, M., & Berkouk, E. M. (2015). A Hybrid PSO-PI based Maximum Power Point Tracking algorithm using adaptive sampling time strategy. In *2015 4th International Conference on Electrical Engineering (ICEE)* (pp. 1–6). IEEE. https://doi.org/10.1109/INTEE.2015.7416787

66. Khalessi, N., Niroomand, M., Dadkhah, J., & Nikouei, S. Y. (2020). A Firework-Based GMPPT with Variable Sampling Time for PV Systems. *Mathematical Problems in Engineering*, 2020. https://doi.org/10.1155/2020/6130202

67. Khan, M. J., Kumar, D., Narayan, Y., Malik, H., Márquez, F. P. G., & Muñoz, C. Q. G. (2022). A Novel Artificial Intelligence Maximum Power Point Tracking Technique for Integrated PV-WT-FC Frameworks. *Energies 2022, Vol. 15, Page 3352*, 15(9), 3352. Retrieved 20 December 2023 from https://doi.org/10.3390/EN15093352

68. Khare, A., & Rangnekar, S. (2013). A review of particle swarm optimization and its applications in Solar Photovoltaic system. *Applied Soft Computing Journal*, 13(5), 2997–3006. https://doi.org/10.1016/j.asoc.2012.11.033

69. Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by simulated annealing. *Science*, 220(4598), 671–680. https://doi.org/10.1126/science.220.4598.671

70. Koad, R. B. A., Zobaa, A. F., & El-Shahat, A. (2017). A Novel MPPT Algorithm Based on Particle Swarm Optimization for Photovoltaic Systems. *IEEE Transactions on Sustainable Energy*, 8(2), 468–476. https://doi.org/10.1109/TSTE.2016.2606421

71. Koh, J. S., Tan, R. H. G., Lim, W. H., & Tan, N. M. L. (2023). A Modified Particle Swarm Optimization for Efficient Maximum Power Point Tracking Under Partial Shading Condition. *IEEE Transactions on Sustainable Energy*, 14(3), 1822–1834. Retrieved 20 December 2023 from https://doi.org/10.1109/TSTE.2023.3250710

72. Kulaksız, A. A., & Akkaya, R. (2012). A genetic algorithm optimized ANN-based MPPT algorithm for a stand-alone PV system with induction motor drive. *Solar Energy*, 86(9), 2366–2375. https://doi.org/10.1016/J.SOLENER.2012.05.006

73. Kumar, N., Hussain, I., Singh, B., & Panigrahi, B. K. (2017a). Maximum Power Peak Detection of Partially Shaded PV Panel by Using Intelligent Monkey King Evolution Algorithm. *IEEE Transactions on Industry Applications*, 53(6), 5734–5743. https://doi.org/10.1109/TIA.2017.2725954

74. Kumar, N., Hussain, I., Singh, B., & Panigrahi, B. K. (2017b). MPPT in Dynamic Condition of Partially Shaded PV System by Using WODE Technique. *IEEE Transactions on Sustainable Energy*, 8(3), 1204–1214. https://doi.org/10.1109/TSTE.2017.2669525

75. Kumar, N., Hussain, I., Singh, B., & Panigrahi, B. K. (2017c). Rapid MPPT for Uniformly and Partial Shaded PV System by Using JayaDE Algorithm in Highly Fluctuating Atmospheric Conditions. *IEEE Transactions on Industrial Informatics*, 13(5), 2406–2416. https://doi.org/10.1109/TII.2017.2700327

76. Kumar, N., Hussain, I., Singh, B., & Panigrahi, B. K. (2018). Normal Harmonic Search Algorithm-Based MPPT for Solar PV System and Integrated With Grid Using Reduced Sensor Approach and PNKLMS Algorithm. *IEEE Transactions on Industry Applications*, 54(6), 6343–6352. https://doi.org/10.1109/TIA.2018.2853744

77. Lal, V. N., & Singh, S. N. (2016). Modified particle swarm optimisation-based maximum power point tracking controller for single-stage utility-scale photovoltaic system with reactive power injection capability. *IET Renewable Power Generation*, 10(7), 899–907. https://doi.org/10.1049/iet-rpg.2015.0346

78. Larbes, C., Aït Cheikh, S. M., Obeidi, T., & Zerguerras, A. (2009). Genetic algorithms optimized fuzzy logic control for the maximum power point tracking in photovoltaic system. *Renewable Energy*, 34(10), 2093–2100. https://doi.org/10.1016/j.renene.2009.01.006

79. Li, G., Jin, Y., Akram, M. W., Chen, X., & Ji, J. (2018). Application of bio-inspired algorithms in maximum power point tracking for PV systems under partial shading conditions – A review. *Renewable and Sustainable Energy Reviews*, 81, 840–873. https://doi.org/10.1016/J.RSER.2017.08.034

80. Li, H., & Liu, L. Q. (2014). A novel particle swarm optimization maximum power point tracking control method based on the direct current voltage superposition principle under partially shaded conditions. *JVC/Journal of Vibration and Control*, 20(9), 1356–1360. https://doi.org/10.1177/1077546312471068

81. Lian, K. L., Jhang, J. H., & Tian, I. S. (2014). A Maximum Power Point Tracking Method Based on Perturb-and-Observe Combined With Particle Swarm Optimization. *IEEE Journal of Photovoltaics*, 4(2), 626–633. https://doi.org/10.1109/JPHOTOV.2013.2297513

82. Liu, L., & Liu, C. (2012). A Novel Combined Particle Swarm Optimization and Genetic Algorithm MPPT Control Method for Multiple Photovoltaic Arrays at Partial Shading. *Journal of Energy Resources Technology*, 135(1), 012002. https://doi.org/10.1115/1.4007940

83. Liu, L., Liu, C., & Gao, H. (2013). A novel improved particle swarm optimization maximum power point tracking control method for photovoltaic array by using current calculated predicted arithmetic under partially shaded conditions. *Journal of Renewable and Sustainable Energy*, 5(6), 063139. https://doi.org/10.1063/1.4858615

84. Liu, L., Meng, X., & Liu, C. (2016). A review of maximum power point tracking methods of PV power system at uniform and partial shading. *Renewable and Sustainable Energy Reviews*, 53, 1500–1507. https://doi.org/10.1016/J.RSER.2015.09.065

85. Liu, Yi Hua, Chen, J. H., & Huang, J. W. (2015). A review of maximum power point tracking techniques for use in partially shaded conditions. *Renewable and Sustainable Energy Reviews*, 41, 436–453. https://doi.org/10.1016/j.rser.2014.08.038

86. Liu, Yi Hwa, Huang, S. C., Huang, J. W., & Liang, W. C. (2012). A particle swarm optimization-based maximum power point tracking algorithm for PV systems operating under partially shaded conditions. *IEEE Transactions on Energy Conversion*, 27(4), 1027–1035. https://doi.org/10.1109/TEC.2012.2219533

87. Lyden, S., & Haque, M. E. (2015a). A hybrid simulated annealing and perturb and observe method for maximum power point tracking in PV systems under partial shading conditions. In *2015 Australasian Universities Power Engineering Conference (AUPEC)* (pp. 1–6). IEEE. https://doi.org/10.1109/AUPEC.2015.7324803

88. Lyden, S., & Haque, M. E. (2015b). Maximum Power Point Tracking techniques for photovoltaic systems: A comprehensive review and comparative analysis. *Renewable and Sustainable Energy Reviews*, 52, 1504–1518. https://doi.org/10.1016/j.rser.2015.07.172

89. Maniezzo, V. (1996). Ant System: Optimization by a Colony of Cooperating Agents, 26(1), 1–13. https://jmvidal.cse.sc.edu/library/dorigo96a.pdf

90. Mao, M., Cui, L., Zhang, Q., Guo, K., Zhou, L., & Huang, H. (2020, November). Classification and summarization of solar photovoltaic MPPT techniques: A review based on traditional and intelligent control strategies. *Energy Reports*. Elsevier Ltd. https://doi.org/10.1016/j.egyr.2020.05.013

91. Mary, S. S., Kumar, S. S., Poluru, S. P., & Reddy, M. J. B. (2015). A dual DC output power supply for a stand-alone photovoltaic system. *Electric Power Components and Systems*, 43(8–10), 939–950. https://doi.org/10.1080/15325008.2015.1012769

92. Maziar Izadbakhsh,Alireza Rezvani, M. G. (2015). Dynamic response improvement of hybrid system by implementing ANN-GA for fast variation of photovoltaic irradiation and FLC for wind turbine. *Archives of Electrical Engineering*, 64(2), 291–314.

93. Meng, Z., & Pan, J. S. (2016). Monkey King Evolution: A new memetic evolutionary algorithm and its application in vehicle fuel consumption optimization. *Knowledge-Based Systems*, 97(C), 144–157. https://doi.org/10.1016/j.knosys.2016.01.009

94. Messai, A., Mellit, A., Guessoum, A., & Kalogirou, S. A. (2011). Maximum power point tracking using a GA optimized fuzzy logic controller and its FPGA implementation. *Solar Energy*, 85(2), 265–277. https://doi.org/10.1016/J.SOLENER.2010.12.004

95. Mirebrahimi SM, S. I. (2016). A Hybrid Intelligent Controlled DC-DC Converter for Photovoltaic energy system application. *Journal of Electrical Engineering*, 16(1). http://www.jee.ro/index.php/jee/article/view/WV1445242177W5624a541f3110

96. Mirhassani, S. M., Golroodbari, S. Z. M., Golroodbari, S. M. M., & Mekhilef, S. (2015). An improved particle swarm optimization based maximum power point tracking strategy with variable sampling time. *International Journal of Electrical Power & Energy Systems*, 64, 761–770. https://doi.org/10.1016/j.ijepes.2014.07.074

97. Mirjalili, S., & Lewis, A. (2016). The Whale Optimization Algorithm. *Advances in Engineering Software*, 95, 51–67. https://doi.org/10.1016/J.ADVENGSOFT.2016.01.008

98. Mirjalili, S., Mirjalili, S. M., & Lewis, A. (2014). Grey Wolf Optimizer. *Advances in Engineering Software*, 69, 46–61. https://doi.org/10.1016/J.ADVENGSOFT.2013.12.007

99. Mitchell, M. (Computer scientist), & Melanie. (1996). *An introduction to genetic algorithms*. MIT Press. https://mitpress.mit.edu/9780262631853/an-introduction-to-genetic-algorithms/

100. Miyatake, M., Veerachary, M., Toriumi, F., Fujii, N., & Ko, H. (2011). Maximum Power Point Tracking of Multiple Photovoltaic Arrays: A PSO Approach. *IEEE Transactions on Aerospace and Electronic Systems*, 47(1), 367–380. https://doi.org/10.1109/TAES.2011.5705681

101. Mohajeri, H. R., Moghaddam, M. P., Shahparasti, M., & Mohamadian, M. (2012). Development a new algorithm for maximum power point tracking of partially shaded photovoltaic arrays. In *20th Iranian Conference on Electrical Engineering (ICEE2012)* (pp. 489–494). IEEE. https://doi.org/10.1109/IranianCEE.2012.6292407

102. Mohanty, S., Subudhi, B., & Ray, P. K. (2016). A New MPPT Design Using Grey Wolf Optimization Technique for Photovoltaic System Under Partial Shading Conditions. *IEEE Transactions on Sustainable Energy*, 7(1), 181–188. https://doi.org/10.1109/TSTE.2015.2482120

103. Mohanty, S., Subudhi, B., & Ray, P. K. (2017). A Grey Wolf-Assisted Perturb & Observe MPPT Algorithm for a PV System. *IEEE Transactions on Energy Conversion*, 32(1), 340–347. https://doi.org/10.1109/TEC.2016.2633722

104. Mohapatra, A., Nayak, B., Das, P., & Mohanty, K. B. (2017). A review on MPPT techniques of PV system under partial shading condition. *Renewable and Sustainable Energy Reviews*, 80, 854–867. https://doi.org/10.1016/j.rser.2017.05.083

105. Morales, R. H., Rohten, J. A., Garbarino, M. N., Munoz, J. A., Silva, J. J., Pulido, E. S., … Andreu, M. L. (2022). A Novel Global Maximum Power Point Tracking Method Based on Measurement Cells. *IEEE Access*, 10, 97481–97494. Retrieved 20 December 2023 from https://doi.org/10.1109/ACCESS.2022.3205163

106. Muthuramalingam, M., & Manoharan, P. S. (2014). Comparative analysis of distributed MPPT controllers for partially shaded stand alone photovoltaic systems. *Energy Conversion and Management*, 86, 286–299. https://doi.org/10.1016/j.enconman.2014.05.044

107. Nusaif, A. I., & Mahmood, A. L. (2020). MPPT Algorithms (PSO, FA, and MFA) for PV System Under Partial Shading Condition, Case Study: BTS in Algazalia, Baghdad. *International Journal of Smart Grid-IjSmartGrid*, 4(3), 100–110. https://www.ijsmartgrid.org/index.php/ijsmartgridnew/article/view/113

108. Oshaba, A. S., Ali, E. S., & Abd Elazim, S. M. (2015). MPPT control design of PV system supplied SRM using BAT search algorithm. *Sustainable Energy, Grids and Networks*, 2, 51–60. https://doi.org/10.1016/J.SEGAN.2015.04.002

109. Pakkiraiah, B., & Sukumar, G. D. (2016). Research Survey on Various MPPT Performance Issues to Improve the Solar PV System Efficiency. *Journal of Solar Energy*, 2016, 1–20. https://doi.org/10.1155/2016/8012432

110. Pathak, P. K., Yadav, A. K., & Alvi, P. A. (2020, August). Advanced solar MPPT techniques under uniform and non-uniform irradiance: A comprehensive review. *Journal of Solar Energy Engineering, Transactions of the ASME*. American Society of Mechanical Engineers (ASME). https://doi.org/10.1115/1.4046090

111. Pattnayak, S. K., Choudhury, S., Nayak, N., Bagarty, D. P., & Biswabandhya, M. (2020). Maximum Power Tracking Harmonic Reduction on grid PV System Using Chaotic Gravitational Search Algorithm Based MPPT Controller. *International Conference on Computational Intelligence for Smart Power System and Sustainable Energy, CISPSSE 2020*, 29–34. https://doi.org/10.1109/CISPSSE49931.2020.9212268

112. Pervez, I., Sarwar, A., Tayyab, M., & Sarfraz, M. (2019). Gravitational Search Algorithm (GSA) based Maximum Power Point Tracking in a Solar PV based Generation System. *2019 Innovations in Power and Advanced Computing Technologies, i-PACT 2019*, 1–6. https://doi.org/10.1109/i-PACT44901.2019.8960130

113. Pious, A., & Rajalakshmi, K. (2014). Optimization of Subcell Interconnection for Multijunction Solar Cells Using DC-DC Converter. *Applied Mechanics and Materials*, 573, 52–58. https://doi.org/10.4028/www.scientific.net/AMM.573.52

114. Prakash, J., Sahoo, S. K., Karthikeyan, S. P., & Raglend, I. J. (2015). Design of PSO-Fuzzy MPPT Controller for Photovoltaic Application (pp. 1339–1348). Springer, New Delhi. https://doi.org/10.1007/978-81-322-2119-7_130

115. Premkumar, M., Kumar, C., Sowmya, R., & Pradeep, J. (2021). A novel salp swarm assisted hybrid maximum power point tracking algorithm for the solar photovoltaic power generation systems. *Automatika*, 62(1), 1–20. https://doi.org/10.1080/00051144.2020.1834062

116. Rajabioun, R. (2011). Cuckoo Optimization Algorithm. *Applied Soft Computing*, 11(8), 5508–5518. https://doi.org/10.1016/j.asoc.2011.05.008

117. Ram, J. P., Babu, T. S., & Rajasekar, N. (2017). A comprehensive review on solar PV maximum power point tracking techniques. *Renewable and Sustainable Energy Reviews*, 67, 826–847. https://doi.org/10.1016/J.RSER.2016.09.076

118. Ramaprabha R, M. B. (2012). Genetic Algorithm Based Maximum Power Point Tracking for Partially Shaded Solar Photovoltaic Array. *International Journal of Research and Reviews in Information Sciences*, 2(1). https://www.researchgate.net/publication/230580963_Genetic_Algorithm_Based_Maximum_Power_Point_Tracking_for_Partially_Shaded_Solar_Photovoltaic_Array

119. Ramaprabha, R., Gothandaraman, V., Kanimozhi, K., Divya, R., & Mathur, B. L. (2011). Maximum power point tracking using GA-optimized artificial neural network for solar PV system. In *2011 1st International Conference on Electrical Energy Systems, ICEES 2011* (pp. 264–268). IEEE. https://doi.org/10.1109/ICEES.2011.5725340

120. Ramdan A. F. Z., K. B. A. (2014). Comparison between the Conventional Methods and PSO Based MPPT Algorithm for Photovoltaic Systems. *International Journal of Electrical, Robotics, Electronics and Communications Engineering*, 8(4), 887–892. https://core.ac.uk/download/pdf/29204074.pdf

121. Ramli, M. A. M., Twaha, S., Ishaque, K., & Al-Turki, Y. A. (2017). A review on maximum power point tracking for photovoltaic systems with and without shading conditions. *Renewable and Sustainable Energy Reviews*, 67, 144–159. https://doi.org/10.1016/j.rser.2016.09.013

122. Rashedi, E., Nezamabadi-pour, H., & Saryazdi, S. (2009). GSA: A Gravitational Search Algorithm. *Information Sciences*, 179(13), 2232–2248. https://doi.org/10.1016/J.INS.2009.03.004

123. Rawat, R., & Chandel, S. (2012). Maximum Power Point Tracking Techniques in Solar Photovoltaic Systems-A Review. In *National Conference on Emerging Technologies in Renewable Energy and Electrical Engineering* (pp. 1–5). Hamirpur.

124. Rawat, R., & Chandel, S. S. (2013a). Hill climbing techniques for tracking maximum power point in solar photovoltaic systems-a review, 90–95.

125. Rawat, R., & Chandel, S. S. (2013b). Review of Maximum-Power-Point Tracking Techniques for Solar-Photovoltaic Systems, 177005, 438–448. https://doi.org/10.1002/ente.201300053

126. REN21. (2018). RENEWABLES 2018 GLOBAL STATUS REPORT. https://www.ren21.net/gsr-2018/

127. Rezk, H., & Dousoky, G. M. (2016). Technical and economic analysis of different configurations of stand-alone hybrid renewable power systems – A case study. *Renewable and Sustainable Energy Reviews*, 62, 941–953. https://doi.org/10.1016/J.RSER.2016.05.023

128. Rezvani, A., Izadbakhsh, M., & Gandomkar, M. (2015). Dynamic modeling of grid-connected photovoltaic system using artificial neural network and genetic algorithm. *Journal of Electrical Systems*, 11(2), 131–144. https://www.researchgate.net/publication/280098649_Dynamic_modeling_of_grid-connected_photovoltaic_system_using_artificial_neural_network_and_genetic_algorithm

129. Rezvani, A., Izadbakhsh, M., & Gandomkar, M. (2016). Microgrid dynamic responses enhancement using artificial neural network-genetic algorithm for photovoltaic system and fuzzy controller for high wind speeds. *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, 29(2), 309–332. https://doi.org/10.1002/jnm.2078

130. Roy Chowdhury, S., & Saha, H. (2010). Maximum power point tracking of partially shaded solar photovoltaic arrays. *Solar Energy Materials and Solar Cells*, 94(9), 1441–1447. https://doi.org/10.1016/j.solmat.2010.04.011

131. Saad, N. H., El-Sattar, A. A., & Mansour, A. E.-A. M. (2016). Improved particle swarm optimization for photovoltaic system connected to the grid with low voltage ride through capability. *Renewable Energy*, 85, 181–194. https://doi.org/10.1016/j.renene.2015.06.029

132. Salam, Z., Ahmed, J., & Merugu, B. S. (2013). The application of soft computing methods for MPPT of PV system: A technological and status review. *Applied Energy*, 107, 135–148. https://doi.org/10.1016/J.APENERGY.2013.02.008

133. Sangeetha, K., Sudhakar Babu, T., & Rajasekar, N. (2016). Fireworks Algorithm-Based Maximum Power Point Tracking for Uniform Irradiation as Well as Under Partial Shading Condition (pp. 79–88). Springer, New Delhi. https://doi.org/10.1007/978-81-322-2656-7_8

134. Saravanan, S., & Ramesh Babu, N. (2016). Maximum power point tracking algorithms for photovoltaic system - A review. *Renewable and Sustainable Energy Reviews*, 57(2), 192–204. https://doi.org/10.1016/j.rser.2015.12.105

135. Sarvi, M., Ahmadi, S., & Abdi, S. (2015). A PSO-based maximum power point tracking for photovoltaic systems under environmental and partially shaded conditions. *Progress in Photovoltaics: Research and Applications*, 23(2), 201–214. https://doi.org/10.1002/pip.2416

136. Seyedmahmoudian, M., Horan, B., Soon, T. K., Rahmani, R., Than Oo, A. M., Mekhilef, S., & Stojcevski, A. (2016). State of the art artificial intelligence-based MPPT techniques for mitigating partial shading effects on PV systems – A review. *Renewable and Sustainable Energy Reviews*, 64, 435–455. https://doi.org/10.1016/j.rser.2016.06.053

137. Seyedmahmoudian, Mohammadmehdi, Mekhilef, S., Rahmani, R., Yusof, R., & Asghar Shojaei, A. (2014). Maximum power point tracking of partial shaded photovoltaic array using an evolutionary algorithm: A particle swarm optimization technique. *Journal of Renewable and Sustainable Energy*, 6(2), 023102. https://doi.org/10.1063/1.4868025

138. Seyedmahmoudian, Mohammadmehdi, Rahmani, R., Mekhilef, S., Maung Than Oo, A., Stojcevski, A., Soon, T. K., & Ghandhari, A. S. (2015). Simulation and Hardware Implementation of New Maximum Power Point Tracking Technique for Partially Shaded PV System Using Hybrid DEPSO Method. *IEEE Transactions on Sustainable Energy*, 6(3), 850–862. https://doi.org/10.1109/TSTE.2015.2413359

139. Shaiek, Y., Ben Smida, M., Sakly, A., & Mimouni, M. F. (2013). Comparison between conventional methods and GA approach for

maximum power point tracking of shaded solar PV generators. *Solar Energy*, 90, 107–122. https://doi.org/10.1016/J.SOLENER.2013.01.005

140. Shankar, G., & Mukherjee, V. (2015). MPP detection of a partially shaded PV array by continuous GA and hybrid PSO. *Ain Shams Engineering Journal*, 6(2), 471–479. https://doi.org/10.1016/J.ASEJ.2014.10.017

141. Shareef, H., Mutlag, A. H., & Mohamed, A. (2017). Random Forest-Based Approach for Maximum Power Point Tracking of Photovoltaic Systems Operating under Actual Environmental Conditions. *Computational Intelligence and Neuroscience*, 2017, 1–17. https://doi.org/10.1155/2017/1673864

142. Shi, J., Zhang, W., Zhang, Y., Xue, F., & Yang, T. (2015). MPPT for PV systems based on a dormant PSO algorithm. *Electric Power Systems Research*, 123, 100–107. https://doi.org/10.1016/j.epsr.2015.02.001

143. Shuying, L., Guodong, Y., Jisheng, L., & Jinyu, L. (n.d.). Simulation of MPPT control using an improved particle swarm optimization algorithm of generation system. *BioTechnology: An Indian Journal*, 10(7). https://www.tsijournals.com/abstract/simulation-of-mppt-control-using-an-improved-particle-swarm-optimization-algorithm-of-generation-system-7985.html

144. Sinha, S., & Chandel, S. S. (2015). Review of recent trends in optimization techniques for solar photovoltaic-wind based hybrid energy systems. *Renewable and Sustainable Energy Reviews*, 50, 755–769. https://doi.org/10.1016/j.rser.2015.05.040

145. Souamy, L. (2012). Research on the MPPT Stability of the Single-Stage and Single-Phase Photovoltaic Grid-Connected System. *Applied Mechanics and Materials*, 263–266, 2252–2257. https://doi.org/10.4028/www.scientific.net/AMM.263-266.2252

146. Sudhakar Babu, T., Rajasekar, N., & Sangeetha, K. (2015). Modified Particle Swarm Optimization technique based Maximum Power Point Tracking for uniform and under partial shading condition. *Applied Soft Computing*, 34, 613–624. https://doi.org/10.1016/j.asoc.2015.05.029

147. Sudhakar Babu, T., Sangeetha, K., & Rajasekar, N. (2016). Voltage band based improved particle swarm optimization technique for maximum power point tracking in solar photovoltaic system. *Journal of Renewable and Sustainable Energy*, 8(1), 013106. https://doi.org/10.1063/1.4939531

148. Sundareswaran, K., Vignesh kumar, V., & Palani, S. (2015). Application of a combined particle swarm optimization and perturb and observe method for MPPT in PV systems under partial shading conditions. *Renewable Energy*, 75, 308–317. https://doi.org/10.1016/J.RENENE.2014.09.044

149. Sundareswaran, K., Vigneshkumar, V., Simon, S. P., & Nayak, P. S. R. (2016). Gravitational search algorithm combined with P&O method for MPPT in PV systems. In *2016 IEEE Annual India Conference (INDICON)* (pp. 1–5). IEEE. https://doi.org/10.1109/INDICON.2016.7838956

150. Sundareswaran, Kinattingal, Palani, S., & Vigneshkumar, V. (2015). Development of a hybrid genetic algorithm/perturb and observe algorithm for maximum power point tracking in photovoltaic systems under non-uniform insolation. *IET Renewable Power Generation*, 9(7), 757–765. https://doi.org/10.1049/iet-rpg.2014.0333

151. Sundareswaran, Kinattingal, Vigneshkumar, V., Sankar, P., Simon, S. P., Srinivasa Rao Nayak, P., & Palani, S. (2016). Development of an Improved P&O Algorithm Assisted Through a Colony of Foraging Ants for MPPT in PV System. *IEEE Transactions on Industrial Informatics*, 12(1), 187–200. https://doi.org/10.1109/TII.2015.2502428

152. Tan, Y., & Zhu, Y. (2010). Fireworks Algorithm for Optimization (pp. 355–364). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-13495-1_44

153. Tang, R. li, Wu, Z., & Fang, Y. jun. (2016). Maximum power point tracking of large-scale photovoltaic array. *Solar Energy*, 134, 503–514. https://doi.org/10.1016/j.solener.2016.05.026

154. Teshome, D. F., Lee, C. H., Lin, Y. W., & Member, K. L. L. S. (2016). A Modified Firefly Algorithm for Photovoltaic Maximum Power Point Tracking Control Under Partial Shading, 6777(c), 1–24. https://doi.org/10.1109/JESTPE.2016.2581858

155. Tian, Z. G., Tian, L., He, J., Huang, Z. H., Zhang, D. H., & Sun, D. Da. (2014). Maximum Power Point Tracking Based on SVR and GA. *Applied Mechanics and Materials*, 687–691, 3231–3234. https://doi.org/10.4028/www.scientific.net/AMM.687-691.3231

156. Troudi, F., Jouini, H., Mami, A., Khedher, N. Ben, Aich, W., Boudjemline, A., & Boujelbene, M. (2022). Comparative Assessment between Five Control Techniques to Optimize the Maximum Power Point Tracking Procedure for PV Systems. *Mathematics 2022, Vol. 10, Page 1080*, 10(7), 1080. Retrieved 20 December 2023 from https://doi.org/10.3390/MATH10071080

157. Vafaei, S., Rezvani, A., Gandomkar, M., & Izadbakhsh, M. (2015). Enhancement of grid-connected photovoltaic system using ANFIS-GA under different circumstances. *Frontiers in Energy*, 9(3), 322–334. https://doi.org/10.1007/s11708-015-0362-x

158. Venkata Rao, R. (2016). Jaya: A simple and new optimization algorithm for solving constrained and unconstrained optimization problems. *International Journal of Industrial Engineering Computations*, 19–34. https://doi.org/10.5267/j.ijiec.2015.8.004

159. Venugopalan, R., Krishnakumar, N., Sarjila, R., & Rajasekar, N. (2013). Application of Particle Swarm Optimization Technique for the Design of Maximum Power Point Tracking. Advanced Materials Research, 768, 47–56. https://doi.org/10.4028/www.scientific.net/AMR.768.47

160. Verma, D., Nema, S., Shandilya, A. M., & Dash, S. K. (2016). Maximum power point tracking (MPPT) techniques: Recapitulation in solar photovoltaic systems. Renewable and Sustainable Energy Reviews, 54, 1018–1034. https://doi.org/10.1016/J.RSER.2015.10.068

161. Wang, L., Wei, X., Zhu, T., & Zhang, J. (2014). Two-Stage Chaos Optimization Search Application in Maximum Power Point Tracking of PV Array. Mathematical Problems in Engineering, 2014, 1–11. https://doi.org/10.1155/2014/464835

162. Wei, L. M., & Li, K. K. (2022). Research on the maximum power point tracking method of photovoltaic based on Newton interpolation-assisted particle swarm algorithm. Clean Energy, 6(3), 496–502. Retrieved 20 December 2023 from https://doi.org/10.1093/CE/ZKAC028

163. Wu, Z., Yu, D., & Kang, X. (2018). Application of improved chicken swarm optimization for MPPT in photovoltaic system. Optimal Control Applications and Methods, 39(2), 1029–1042. https://doi.org/10.1002/oca.2394

164. Yadav, A. K., & Chandel, S. S. (2013). Tilt angle optimization to maximize incident solar radiation: A review. Renewable and Sustainable Energy Reviews, 23, 503–513. https://doi.org/10.1016/j.rser.2013.02.027

165. Yang, B., Zhu, T., Wang, J., Shu, H., Yu, T., Zhang, X., … Sun, L. (2020, September). Comprehensive overview of maximum power point tracking algorithms of PV systems under partial shading condition. Journal of Cleaner Production. Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.121983

166. Yang, X. S. (2010). A new metaheuristic Bat-inspired Algorithm. Studies in Computational Intelligence, 284, 65–74. https://doi.org/10.1007/978-3-642-12538-6_6

167. Yang, X., Deb, S., & Behaviour, a C. B. (2009). Cuckoo Search via L ´ evy Flights. World Congress on Nature & Biologically Inspired Computing, 210–214. http://arxiv.org/abs/1003.1594

168. Yang, X.-S. (2008). Nature-inspired metaheuristic algorithms. https://staff.fmi.uvt.ro/~daniela.zaharie/ma2016/projects/techniques/FireflyAlgorithm/Yang_nature_book_part.pdf

169. Yifei Zheng, Chun Wei, & Shaobo Lin. (2011). A maximum power point tracking method based on tabu search for PV systems under partially shaded conditions. In IET Conference on Renewable Power Generation (RPG 2011) (pp. 52–52). IET. https://doi.org/10.1049/cp.2011.0119

170. Zagrouba, M., Sellami, A., Bouaïcha, M., & Ksouri, M. (2010). Identification of PV solar cells and modules parameters using the genetic algorithms: Application to maximum power extraction. Solar Energy, 84(5), 860–866. https://doi.org/10.1016/j.solener.2010.02.012

171. Zhang, L., & Bai, Y. F. (2008). On-line neural network training for maximum power point tracking of PV power plant. Transactions of the Institute of Measurement and Control, 30(1), 77–96. https://doi.org/10.1177/0142331207076374

172. Zhao, Y., Zhao, X., & Zhang, Y. (2014). MPPT for Photovoltaic System Using Multi-objective Improved Particle Swarm Optimization Algorithm. TELKOMNIKA Indonesian Journal of Electrical Engineering, 12(1). https://doi.org/10.11591/telkomnika.v12i1.3965