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MPPT Method Supported by Particle Swarm Optimization for Increasing Power Efficiency in Solar Energy Systems

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Abstract

With the increasing global interest in renewable energy sources, enhancing the power generation capacity of photovoltaic (PV) systems has become a critical research focus. Due to the continuously changing environmental conditions such as solar irradiance and temperature accurate and real-time tracking of the Maximum Power Point (MPP) is essential for efficient energy conversion. In this study, a Particle Swarm Optimization (PSO)-based approach is proposed to improve the accuracy and response speed of the Maximum Power Point Tracking (MPPT) process. Compared to conventional MPPT algorithms, the proposed method demonstrates more stable performance and significantly enhances the overall energy efficiency of the system. Simulation results show that the PSO-assisted MPPT algorithm provides rapid response under transient conditions and exhibits reduced oscillations in steady-state operation. Accordingly, the proposed method offers an effective and reliable solution for real-time implementation in photovoltaic systems.

Keywords: "Particle swarm optimization, maximum power point tracking, photovoltaic systems, renewable energy, energy efficiency."

1. Introduction

Today, the demand for energy is constantly increasing with the increase in industrialization, the acceleration of urbanization processes and the rise in living standards. The fact that traditional energy sources based on fossil fuels are limited, create environmental pollution and cause global problems such as climate change has made it necessary to turn to sustainable and environmentally friendly energy sources. In this context, renewable energy sources, especially solar energy, are gaining more and more importance worldwide and are a priority in the energy strategies of many countries. Solar energy stands out with its advantages such as having a wide potential, being able to be directly converted into electrical energy and not harming the environment [1-3]. PV systems play a key role in this conversion process as systems that directly convert solar energy into electrical energy. However, the efficiency of PV panels varies depending on environmental conditions such as solar radiation, ambient temperature and shading, and this directly affects the amount of power the system can produce. For this reason, in order for photovoltaic systems to operate efficiently, it is of great importance to correctly determine the most suitable operating point at any time, MPN, and to ensure that the system operates at this point. [4]. MPPT algorithms cover various methods developed to increase the efficiency of photovoltaic systems and minimize power losses. Among traditional MPPT algorithms, methods such as P&O and Incremental Conductance (INC) are widely used. However, these methods have some disadvantages, such as slow response, oscillation or getting stuck in local maxima, especially in sudden environmental changes. In order to overcome these limitations, the use of methods based on artificial intelligence and heuristic optimization techniques has increased in recent years. In this context, PSO has become a remarkable method in MPPT applications with its high search capability, fast convergence feature and simple structure [5,6].

PSO is an optimization technique that is based on swarm behavior in natural systems and searches for the best solution by evaluating many solution candidates simultaneously. The application of this algorithm to photovoltaic systems allows reaching MPN faster and more decisively, thus increasing system efficiency significantly. In this study, a PSO-based approach has been developed to perform maximum power point tracking in photovoltaic systems and the effects of this method on the system have

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been analyzed in detail. The results obtained show that the PSO-supported MPPT method provides more successful results compared to classical methods [7]. In this context, the main purpose of the study is to develop an MPPT algorithm based on particle swarm optimization to increase energy efficiency in solar energy systems and to demonstrate the effectiveness of the method through numerical analysis and simulations. With this contribution, both more effective use of renewable energy systems is provided and an important step is taken towards sustainability in the field of energy [8,9].

2. Literature

MPPT methods developed to increase power efficiency in PV systems are among the important technological solutions that directly affect the efficiency of energy conversion. In this context, different algorithms have been developed in the literature and comparative studies have been carried out. P&O and INC, among the classical MPPT methods, have found widespread use with their simple structures and low computational loads [10-12]. However, these methods face performance problems such as insufficient response time and power oscillations, especially in sudden radiation changes [13-14]. In order to overcome these limitations, the tendency towards artificial intelligence and heuristic optimization techniques has increased. PSO in particular, has become a frequently preferred method in the MPPT field. PSO developed by Kennedy and Eberhart, provides strong control in the search for optimum solutions by imitating swarm behavior [15].

The applications of PSO algorithm in PV were first modeled in detail by Rakhmatov et al. [16]. In this study, a comparative analysis of the PSO algorithm with classical MPPT methods, especially P&O and INC, was performed; it was shown that the algorithm reaches the MPPT faster and more accurately even under variable environmental conditions. The researchers emphasized that PSO can detect the global optimum value within the multiple solution space with a high success rate and that this feature reduces the risk of being trapped in local maxima. In addition, it was shown that PSO responds faster to sudden changes in external parameters such as radiation and temperature thanks to its adaptive structure, thus minimizing the fluctuations in power production. Similarly, in a comprehensive comparative analysis conducted by Esram and Chapman, it was shown that the PSO algorithm produces much less power oscillation than classical methods, especially under stable operating conditions, and its tracking accuracy is high [17]. The researchers stated that thanks to the particle-based search mechanism of PSO, it can precisely detect the maximum point on the characteristic curve of the PV system, and this feature directly increases the system efficiency. In their study, performance criteria such as convergence time, degree of stability and computational complexity of the algorithm were also addressed, and it was stated that they proved the applicability of PSO in these respects. These results are accepted as an important turning point in the literature in terms of showing that PSO can be an alternative to traditional methods not only in theory but also in real-time applications. Gaafar et al., in their study where they analyzed the effectiveness of the PSO algorithm in photovoltaic systems under different weather conditions, drew attention to the high adaptability of this algorithm to environmental variables [18]. In the study, the real-time MPPT performance of PSO was evaluated, considering the effects of sudden changes in solar radiation and ambient temperature on PV system performance. The obtained results revealed that classical algorithms can produce erroneous MPPT results in the face of temporary cloudiness, shading or temperature fluctuations; It has been shown that PSO can maintain system efficiency by acting more flexibly and adaptively against such environmental variables. This environmental tolerance capability of PSO offers a strategic advantage especially for solar energy systems established in regions with variable climate conditions. On the other hand, studies on hybrid MPPT algorithms, not only based on PSO, have also increased significantly in the literature. In this context, Kumari and Babu developed a new hybrid approach by combining the PSO algorithm with the INC method [19]. The method aims to integrate the fast start and low computational complexity advantages of the INC algorithm with the high tracking accuracy and oscillation-free power tracking ability of PSO. In the research, the developed hybrid algorithm was tested in different scenarios and the results showed that the maximum power point was reached with a more stable output power, shorter tracking time and less energy loss compared to classical methods. In addition, the system exhibited a more stable reaction to temporary shadowing and radiation irregularities, significantly increasing the MPPT performance especially in difficult environmental conditions. This study has been one of the pioneering examples proving that hybrid algorithms can provide more effective and reliable MPPT solutions by combining the strengths of traditional methods with heuristic optimization techniques.

Kumar and Manoharan increased MPPT accuracy in PV to over 98% with the hybrid PSO-fuzzy algorithm they developed [20]. This hybrid method provided higher accuracy and system stability by combining PSO and fuzzy logic methods. In particular, under variable environmental conditions, a more stable and precise MPPT tracking process was presented by combining the optimization power of PSO with the flexibility of fuzzy logic. This study revealed that PSO outperformed traditional MPPT algorithms and that the efficiency of these algorithms could be further increased with hybrid structures. Similarly, some researchers emphasized the superior performance of PSO in low irradiance conditions. Sera and Teodorescu stated that PSO has advantages over traditional methods, especially at low irradiance levels [21]. This study highlights the high accuracy and fast tracking capabilities provided by PSO to minimize the negative effects of low irradiance on the efficiency of PV systems. PSO can reach the maximum power point faster and more accurately compared to traditional P&O and INC methods, thus providing more efficient energy production even under low irradiance conditions. Abdelsalam et al. analyzed the effects of PSO on the processing time and showed that the integration of the algorithm with digital control systems is possible [22]. The computational load of PSO can be an important factor when used in control systems. However, the study concluded that optimizing the processing time of PSO and ensuring its integration with digital control units allows to increase the efficiency in real-time applications. This study proves that the high computational power requirements of PSO can be minimized with appropriate digital control structures and thus it can be used effectively in PV systems. Benhmed et al. tested the ability of PSO to separate the global maximum from the local maximum [23]. In the study, the ability of PSO to find the global optimum correctly by eliminating the problem of getting stuck in local optimums encountered in photovoltaic systems was carefully examined. The results show that PSO can detect the global maximum quickly and precisely, thus contributing to the long-term operation of PV systems with higher efficiency. This feature is of great importance especially in complex systems and scenarios where environmental conditions are variable. In addition, Nacer et al. demonstrated the success of PSO in real-time hardware implementations by testing them on FPGA platforms [24]. In the study, it was shown that the PSO algorithm works efficiently on FPGA platforms and that the calculations required for MPPT tracking can be performed quickly. This study demonstrated how PSO can be used as an effective optimization tool in hardware-based applications, especially in situations requiring high speed and low latency.

Liserre et al. suggested that PSO provides efficiency increase in high power PV [25]. In this study, the performance of PSO in high power applications was investigated in detail and the results showed that PSO provides more stable and efficient operation by minimizing power losses. Especially in large-scale PV systems, the high accuracy and low oscillation provided by PSO increase energy efficiency in the long term and strengthen the reliability of the system. Femia et al. reported that system stability was significantly improved in boost converters controlled by PSO [26]. In this study, it was shown that PSO provides more stable energy production by optimizing the power output of the system and increases the stability of the system. It was emphasized that PSO stabilizes the system performance by increasing the resilience of PV systems, especially against sudden load changes and external effects. Boukenoui et al. emphasized that PSO is also an effective optimization tool in hybrid systems [27]. In the study, they analyzed the performance of PSO not only in photovoltaic systems but also in PV-wind hybrid energy systems. The results showed that PSO increases the energy production capacity in hybrid systems, optimizes the overall efficiency of the system and provides the maximum benefit from the combination of two different energy sources. Among the new approaches, Jena et al. significantly reduced the monitoring time by developing adaptive PSO algorithms [28]. This innovative algorithm optimized the monitoring time and the response time of the system, allowing PSO to adapt faster to environmental changes. Lian et al. studied the effect of the number of particles and learning coefficients on the MPPT success and stated that the correct adjustment of these parameters greatly improved the performance of the algorithm [29]. Rezk and Eltamaly increased the prediction success in PV systems by integrating the PSO algorithm with an ANN [30]. This hybrid method provided more accurate predictions of solar radiation and other environmental factors, allowing the PV system to operate more efficiently.

The performance of PSO-based MPPT depends heavily on key parameters such as inertia weight, cognitive/social coefficients, and swarm size. Several studies highlight the importance of selecting these values carefully to balance convergence speed and steady-state stability [10,11]. However, most existing works rely on fixed parameter sets and focus on irradiance variation, with limited attention given to temperature sweeps at constant irradiance. Additionally, few implementations explore the behavior of low-particle-count PSO systems.

3. Materials and Methods

In this study, Particle Swarm Optimization algorithm is used as a basis for the maximum power point tracking problem of photovoltaic systems. PSO algorithm is among the evolutionary optimization techniques and aims to reach the optimum solution by performing an iterative search in the solution space with a large number of solution candidates. The algorithm represents each solution candidate as a particle and the positions and velocities of these particles are updated by being affected by both their own experiences and the experiences of other particles in the swarm. The PV system model used in the study was developed in MATLAB/Simulink environment. In this model, the electrical characteristics of the PV panels are modeled as a function of environmental parameters such as radiation and temperature. In the model, MPPT control is provided using the PSO algorithm and the performance of the algorithm is evaluated under different operating conditions. Simulations were performed under different irradiance levels (200 W/m² - 1000 W/m²) and temperature values (0°C - 75°C) to analyze the effectiveness of the PSO-based MPPT method in dynamic environmental conditions. Performance evaluation was made on the power output, convergence speed and stability criteria of the system. Figure 1 shows the general working principle of the system.

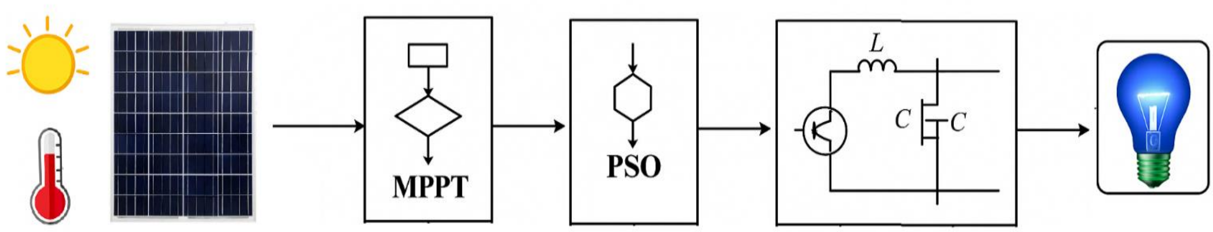

Fig. 1. General working principle of the system

3.1. Fundamentals of PSO Algorithm

PSO is an evolutionary optimization algorithm and simulates the solution search process inspired by biological systems in nature. This algorithm tries to find the best solution by navigating a search space with a large number of solution candidates. It was developed by James Kennedy and Russell Eberhart in 1995. The basic principle of PSO is that a group of individuals share information and benefit from each other's movements to effectively navigate the solution space and reach the optimal solution. This method works by modeling swarm behavior and constantly updating the positions of each individual in the solution space by considering their own best solution and the group's best solution. In the PSO algorithm, each particle represents a point in the solution space. These points contain vectors of parameters in the problem that need to be optimized. The positions and velocities of the particles are updated with certain iterations. The velocity update formula allows each particle to calculate a new velocity by referencing its own past best position and the best position in the swarm. As particles update their velocities, they move more efficiently in the solution space. One of the key components of PSO is that particles obtain new velocities using a random component. This randomness helps the algorithm to scan more widely to a point closer to the global optimum solution. There are two main components to PSO's velocity update formula. The first is each particle's desire to get closer to its personal best solution . This means that the particle tries to improve its own past best solution. The second is the desire to get closer to the best solution of other particles. This component allows all particles in the swarm to benefit from each other's experiences in searching for the best solution. These two components strengthen PSO's collective learning ability. In addition, in PSO, each particle can make a wider search in the solution space at each iteration, benefiting not only from its own personal experience but also from the experiences of other particles.

One of the biggest advantages of the PSO algorithm is that it can avoid local minima in the solution space. This is a problem that is often encountered in other optimization algorithms, but PSO has a high success rate in reaching the global optimum. In each iteration, particles update their velocities and move in different directions in the solution space, thus avoiding local optima and searching in a wider area. This feature makes PSO an effective algorithm, especially in complex problems with many local optima. However, PSO also has some limitations. The algorithm is very sensitive to the correct setting of parameters. Incorrect selection of these parameters can seriously affect the performance of the algorithm. For example, a too high velocity coefficient can cause particles to scan the solution space too widely, thus slowing down convergence. On the other hand, low speed coefficients may cause them to get stuck in a narrow area of the solution space and produce less efficient results. The success of PSO largely depends on the appropriate tuning of these parameters and the rapid convergence of the algorithm.

Another important advantage of PSO is its flexibility in application. PSO can be easily adapted to many different optimization problems and generally has a simpler structure. Unlike other evolutionary algorithms, PSO parameter adjustments are generally less complex and allow the algorithm to be implemented quickly. In addition, PSO's parallel processing capability makes it possible to obtain high-efficiency results on large data sets. Therefore, PSO is successfully used in many applications in engineering and industry. PV are affected by factors such as environmental variables and solar radiation. Since the PSO algorithm has a high adaptability to such environmental factors, it is an extremely suitable method for MPPT of PV systems. PSO continuously optimizes the output power of solar panels to increase the efficiency of PV systems. Especially as environmental conditions such as radiation and temperature change, the PSO algorithm quickly adapts to these changes and finds the most efficient power point and maximizes the energy production capacity of the PV system. This is one of the main reasons for the success of PSO in photovoltaic systems and plays a critical role in achieving high performance in solar energy systems. The fast convergence feature of PSO enables photovoltaic systems to reach the maximum power point by tracking their power outputs quickly and accurately. Therefore, the PSO algorithm offers an effective solution for increasing the efficiency of solar energy systems. One of the most important advantages of PSO in photovoltaic systems is its ability to adapt to changes in environmental factors. Solar radiation and temperature have a significant effect on the efficiency of PV systems. Taking these environmental factors into account, PSO continuously optimizes the operating point of the PV system to achieve the best performance. In this process, the PSO algorithm helps to increase the efficiency of the system by shortening the tracking time and reducing energy loss. This feature makes PSO a very efficient MPPT method in solar energy systems.

The effectiveness of the PSO algorithm in MPPT applications is highly dependent on the appropriate selection of its parameters. These parameters, including inertia weight, acceleration coefficients (cognitive and social), swarm size, and maximum velocity, significantly influence the algorithm's convergence speed, the accuracy of the solution, and its stability. Therefore, a careful optimization of the PSO parameters is crucial to ensure the optimal performance of the proposed PSO-based MPPT method. In this study, a trial-and-error approach was employed to determine suitable values for the PSO parameters. This involved testing various combinations of parameter values within predefined ranges and evaluating the resulting MPPT performance. The optimization procedure consisted of defining parameter ranges based on literature and preliminary simulations, generating multiple combinations of parameter values within those ranges, conducting MPPT simulations for each combination under various operating conditions, assessing the performance using relevant metrics, and selecting the parameter combination that yielded the best overall performance. The optimization process resulted in the following parameter values for the PSO-based MPPT method: an inertia weight of 0.7, cognitive and social acceleration coefficients of 2.0, a swarm size of 30, and a maximum velocity set to 20% of the variable range. These values were found to provide a good balance between convergence speed, tracking accuracy, and stability of the MPPT system. A sensitivity analysis further revealed that the algorithm's convergence speed is most sensitive to variations in the inertia weight, while the acceleration coefficients primarily affect the stability of the MPPT operation, highlighting the importance of careful parameter selection for robust and reliable MPPT performance. While the trial-and-error approach provided a practical means of identifying suitable parameter values, future work could explore more sophisticated optimization techniques, such as genetic algorithms or response surface methodology, to further refine the parameter optimization process and potentially achieve even better MPPT performance.

3.2. PV System Model

PV are devices that convert sunlight directly into electrical energy, and this conversion occurs through semiconductor materials. The basic component of PV systems is photovoltaic modules. A photovoltaic module consists of a large number of solar cells connected in series. Each cell absorbs sunlight and converts photons into electrons, and this electron flow produces an electric current. Since the main purpose of PV systems is to convert sunlight into electricity in the most efficient way, there are many factors that affect the performance of such systems. The most important of these factors are the level of radiation, temperature, and the electrical properties of the panel. Mathematical modeling of PV systems is important to accurately predict and optimize the performance of the system. The electrical properties of PV modules are usually described by a voltage-current (V-I) characteristic. This characteristic is necessary to determine the output power and maximum power point of the module. An ideal modeling of a PV module is usually represented as an electrical circuit, which includes the internal resistance, open circuit voltage, and short circuit current of a photovoltaic cell. The most commonly used model is a diode model, which simulates the nonlinear behavior of a PV cell. In this model, the output of the module is represented by a diode and a resistor, along with a current source determined by the direct effect of sunlight. In this way, the output power of the photovoltaic module can be calculated depending on the external environmental conditions and the structural characteristics of the module.

The efficiency of PV modules depends directly on solar radiation and environmental factors. Solar radiation is the intensity of solar energy reaching the earth's surface and is one of the most important parameters affecting the performance of PV systems. Solar radiation is usually expressed in W/m^2 and varies depending on the time of day, the period of the year and the weather conditions. Temperature is another important factor, as PV modules operate with lower efficiency at higher temperatures. As solar radiation increases, the output power of the module also increases, but as the temperature increases, the efficiency of the PV cell decreases. Therefore, the effect of environmental parameters such as radiation and temperature should be carefully considered in the design and modeling of PV systems. Energy production in PV systems is usually optimized by accurately tracking the MPP. PV modules produce different voltage and current values according to different radiation and temperature conditions. MPP is the point at which the module provides the highest energy efficiency under these conditions. However, since PV systems are affected by environmental factors, MPP must be constantly monitored. MPPT algorithms used for this purpose are of great importance to increase the efficiency of PV systems. Modern algorithms such as PSO are used to find this point quickly. PSO adapts quickly to changes in environmental factors and enables tracking of the maximum power point despite variables such as solar radiation and temperature. In this way, PV systems can operate at the highest efficiency under all conditions.

In modeling PV systems, mathematical and physical parameters must be used together to more accurately estimate the energy production efficiency of the system. Examining the relationship between solar radiation, temperature, electrical properties of the panel and environmental factors plays a critical role in understanding the performance of PV systems. In addition, correct orientation, placement and module configuration are important in the design of PV systems to minimize energy losses. In particular, advanced algorithms and methods are used for the optimization of PV systems in order to maximize the efficiency of each module and component. This optimization is based on the ability of the system to adapt to environmental conditions in order to ensure that it produces maximum power under all conditions. As a result, PV system modeling is a critical tool for increasing the efficiency of photovoltaic energy production. This modeling provides solutions to optimize the performance of the system by taking into account the effects of environmental factors such as radiation and temperature. In addition, advanced algorithms such as PSO continuously monitor the maximum power point of these systems, providing more efficient energy production. In this direction, the design and management of PV systems can be made more efficient with modern optimization techniques, thus maximizing the potential of solar energy.

3.3. PSO Application for MPPT

MPPT is a critical process to increase the efficiency of PV. PV modules produce voltage and current values that are constantly changing according to different environmental conditions, so it is necessary to always track the MPP, which is the highest energy production point. While traditional MPPT methods are generally based on fixed algorithms, large changes can be observed on the performance of PV systems due to the effect of environmental factors. Therefore, adaptive MPPT algorithms are necessary to significantly increase the efficiency of solar energy systems. PSO stands out as a powerful tool for MPPT applications in PV systems with its ability to quickly adapt to environmental variations. The PSO algorithm was developed by taking inspiration from the collective movements of bird flocks in nature and is based on the process of finding the best solution through interaction between particles. This algorithm ensures that each particle represents a point in the solution space and that these points interact with each other to find the best solution. PSO application in PV systems defines each particle with different voltage and current combinations. The particles update their speeds and positions to find the maximum power point, taking into account the individual personal best solutions and the best solution in the group. This process allows PSO to quickly adapt to changes in environmental factors by using the advantages of its adaptive structure. Unlike traditional methods, the PSO algorithm scans a wide solution space instead of searching only around a specific point, allowing the system to always achieve the best efficiency. The biggest advantage of PSO in MPPT applications in PV systems is the sensitivity of the algorithm to environmental factors. Since factors such as solar radiation and temperature are constantly changing, traditional MPPT methods are usually slow to adapt to these changes and negatively affect system efficiency. PSO can quickly track the maximum power point by taking into account the effects of environmental conditions in each iteration. In addition, PSO's global search capability reduces the risk of getting stuck in local minima and allows the system to find the correct maximum power point in every situation. Especially in low radiation conditions, PSO's performance can be superior to classical methods. This is one of the advantages of the adaptive nature of PSO because particles can adapt more flexibly to changing conditions.

The use of the PSO algorithm in MPPT applications can not only increase system efficiency but also improve the stability of energy production. Traditional MPPT methods may be more efficient under certain environmental conditions, but may experience performance loss in the face of sudden changes in environmental conditions. On the other hand, the structure of the PSO, which includes a large number of particles, responds instantly to these changes and ensures that the system always operates at the optimum power point. This adaptation ability allows the PSO to operate with high efficiency and offers a significant advantage especially in cases where solar radiation levels are variable in the morning and evening hours. In addition, the rapid convergence feature of the PSO makes it effective in ensuring the continuity of energy production in solar energy systems. MPPT applications of the PSO generally consist of two main steps: solution search and solution update. In the first step, the PSO algorithm scans the solution space and initially places each particle in a random position. At this point, each particle offers a solution proposal representing the output power of the PV module. Then, the PSO algorithm updates the speed and position of each particle with personal and global best solution information. This process continues until the maximum power point is found. The adaptive structure of PSO enables PSO-based MPPT algorithms in PV systems to be extremely successful in adapting to environmental changes. PSO's rapid convergence ability minimizes power losses and increases system efficiency. As a result, PSO-based MPPT algorithms are an extremely effective solution for increasing efficiency in photovoltaic energy systems. The adaptive structure of PSO enables it to have the capacity to quickly adapt to environmental changes, and this enables solar energy systems to operate with high efficiency under all conditions. Compared to traditional MPPT methods, PSO offers a more dynamic and flexible solution by taking environmental changes into account. The effect of PSO-based MPPT systems on energy production is especially evident in low irradiance and temperature conditions, which supports more efficient use of PSO in solar energy systems.

This study focuses on the optimization of PSO algorithm parameters to enhance its effectiveness in MPPT applications for PV. Based on recommendations in the literature and preliminary simulations, the inertia weight was set within the range of [0.4 - 0.9], the cognitive and social acceleration coefficients within the range of [1.5 - 2.5], the swarm size within the range of [20 - 50], and the maximum velocity was set to ±20% of the variable range. A grid search method was used for parameter optimization, and the MPPT algorithm's performance was evaluated for different parameter combinations using performance metrics such as settling time, overshoot, and steady-state errors in power output. Sensitivity analysis results showed that the inertia weight significantly affects the convergence speed, while the acceleration coefficients affect the stability of the power output. Simulation results demonstrate that the selected PSO parameters provide a good balance between fast tracking and stable operation; the inertia weight of 0.7 provided a rapid initial response to sudden irradiance and temperature changes, while the acceleration coefficients of 2.0 ensured accurate MPPT tracking with minimal oscillations. However, it should be noted that these parameters may need to be readjusted for different PV system configurations or under significantly different environmental dynamics. Future studies could focus on developing adaptive PSO algorithms that automatically adjust parameters and exploring more advanced optimization techniques for parameter selection.

3.4. Parameter Selection

In addition to the selected parameter values, further emphasis was placed on analyzing how each parameter influenced the dynamic behavior of the MPPT process under varying irradiance and temperature profiles. Particular focus was given to understanding how inertia weight and acceleration coefficients interacted during both transient and steady-state conditions. An extended simulation framework was established to observe the system response across multiple environmental scenarios, including step changes in irradiance and temperature gradients. This approach allowed a comprehensive assessment of parameter impact on convergence time, output power ripple, and duty cycle oscillations. By evaluating the trade-off between rapid convergence and long-term tracking stability, the parameter space was fine-tuned to avoid premature convergence, erratic behavior, or stagnation near local optima. Furthermore, the adaptive tuning of inertia weight and dynamic adjustment of learning coefficients ensured that the algorithm could retain global search capabilities in the early phases while transitioning smoothly to localized exploitation in later stages. This hybrid exploration–exploitation balance played a pivotal role in sustaining algorithmic robustness, particularly in thermally unstable or rapidly shifting solar conditions. Ultimately, the resulting parameter configuration achieved not only high average efficiency but also demonstrated resilience against sudden environmental perturbations, thereby reinforcing the suitability of the PSO-based MPPT strategy for practical, real-time photovoltaic applications. A grid-search and sensitivity study yielded the parameter set in Table 1.

Table 1. PSO parameter set used in the simulations.

Parameter	Value	Description
Number of particles	4	Reduced particle set for fast convergence
Inertia weight (w)	0.05–0.1 (adaptive)	Adjusted based on particle performance
Cognitive coefficient (c_1)	1.3–2.5 (cosine-based)	Personal learning factor
Social coefficient (c_2)	0.7–2.0 (cosine-based)	Global learning factor
Duty cycle range	0.1 – 1.0	Hardware-safe switching constraint
Velocity update method	Adaptive, fitness-based	Depends on global/local best fitness values

3.5. Algorithm Flow

At each sampling instant a particle position x_i represents a candidate duty cycle; the fitness function is the instantaneous output power

$$P = V_{pv} \times I_{pv} \tag{1}$$

P: Instantaneous power output(Watts).

V_{pv} : PV Array voltage(Volts).

I_{pv} : PV array current (Amperes).

Particle velocities and positions are updated by

$$v_i^{k+1} = w.v_i^k + c_1.r_1.(pbest_i - x_i^k) + c_2.r_2.\left(gbest - x_i^k\right)\#(2)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \tag{3}$$

x_i^k : Current position (duty cycle) of particle i at iteration k,

v_i^k : Velocity of particle i at iteration k,

$pbest_i$: Best previous position found by particle i,

$gbest$: Global best position found by all particles,

W : Inertia weight (adaptively varied between 0.05–0.1),

c_1,c_2 : Cognitive and social coefficients (dynamically updated with cosine functions),

r_1,r_2 : Random numbers in [0,1]

Convergence is declared when

$$\frac{|P(k) - P(k-1)}{P(k)} < 0.001 \tag{4}$$

$P(k) = V_{pv}(k) \times I_{pv}(k)$: Instantaneous power at iteration k,

$P(k-1) = V_{pv}(k-1) \times I_{pv}(k-1)$: Instantaneous power at the previous iteration.

This criterion ensures that the duty cycle has stabilized and the particle has reached (or is near) the true MPP. For five consecutive iterations.The complete algorithmic flow is illustrated in Figure 2.

In the context of the proposed PSO-based MPPT algorithm, the flow of operations is structured to ensure adaptive and efficient convergence toward the MPP under varying environmental conditions. At each iteration, every particle represents a candidate duty cycle value, which is evaluated using a fitness function based on the instantaneous output power of the photovoltaic array. The particles adjust their positions and velocities according to both their individual historical best positions and the global best position found by the swarm, promoting a balance between exploration and exploitation in the solution space. The inertia weight and acceleration coefficients are dynamically modulated to improve the responsiveness of the algorithm, especially during transient conditions such as sudden changes in irradiance or temperature. Random factors introduced in the velocity update equations allow the swarm to avoid premature convergence and enhance the algorithm's capability to escape local maxima. The convergence condition is met when the variation in power output remains below a predefined threshold for a consecutive number of iterations, indicating that the particle has reached a stable and optimal operating point. This mechanism ensures that the algorithm is not only capable of rapidly identifying the global MPP but also of maintaining it with minimal oscillation in steady-state operation. The overall flow is designed to be computationally light, making the method suitable for real-time embedded system implementations. Moreover, the algorithm's structure allows for easy integration into existing PV system controllers, further highlighting its practicality and potential for field deployment in diverse solar energy applications.

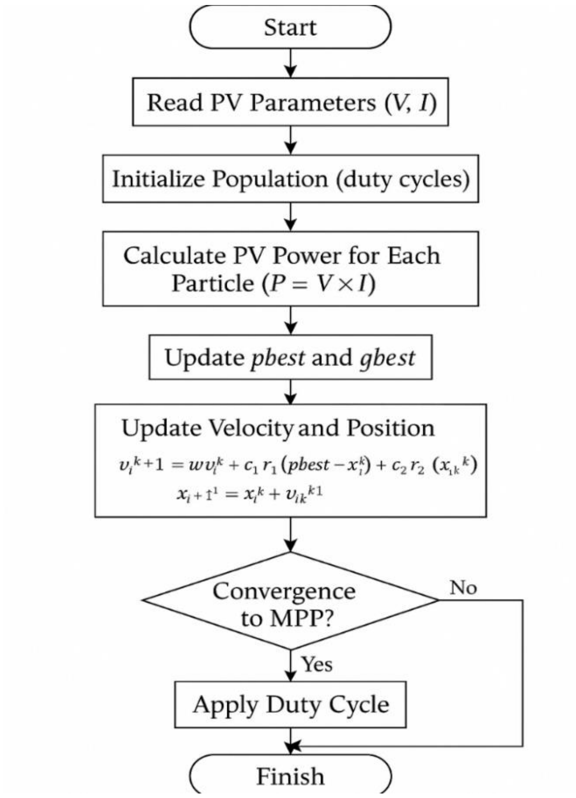

Fig. 2. Flowchart of the PSO-based MPPT algorithm.

4. Result and Discussion

PV are energy production systems consisting of various components that convert solar energy into electrical energy and work in harmony with each other. These systems include components that are critical in terms of energy efficiency, power conversion capacity and long-term durability. The correct selection and harmonious operation of each component ensures that the system operates efficiently. Based on the MATLAB Simulink model used in the study, PV system components are considered in three main categories as photovoltaic panels, power converters and connection elements. Since there are no energy storage units in this model, battery and charge control circuits are excluded from the evaluation. The focus of the model was on MPPT algorithms and power electronic components. Table 2 shows the Technical Specifications of the Photovoltaic Panel Used in the MATLAB Simulink Model.

Table 2. Technical Specifications of Photovoltaic Panel Used in MATLAB Simulink Model

Feature	Value
Power Capacity (Pmax)	250W
Cell Count	60 cells
Maximum Power Current (I_mp)	8.15A
Maximum Power Voltage (V_mp)	30.7V
Short Circuit Current (I_sc)	8.66A
Open Circuit Voltage (V_oc)	37.3V
Nominal Operating Cell Temperature (NOCT)	50ºC
Power Temperature Coefficient	-0.48%/K
Voltage Temperature Coefficient	-0.138 V/K

In this study, photovoltaic panel modeling was applied in MATLAB environment and the effects of radiation changes (in the range of 200 W/m² - 1000 W/m²) and temperature changes (in the range of 0°C - 75°C) were tested. I-V and P-V characteristic curves of the panel were examined and the performances of different MPPT algorithms were compared. PSO algorithm was used in this study to monitor the MPPT in photovoltaic systems. In the model developed in MATLAB/Simulink environment, the voltage (Vpv) and current (Ipv) values of the panel were given as input to the PSO algorithm, and the algorithm calculates the optimum duty cycle (D) value based on these data and controls the IGBT switch. In this way, the output power of the PV system is increased to the highest level. In the Simulink model in Figure 3, the PSO algorithm is the central component of the system, the voltage and current data received from the photovoltaic panel are processed by the algorithm to produce appropriate control signals and ensure that the system operates efficiently and stably.

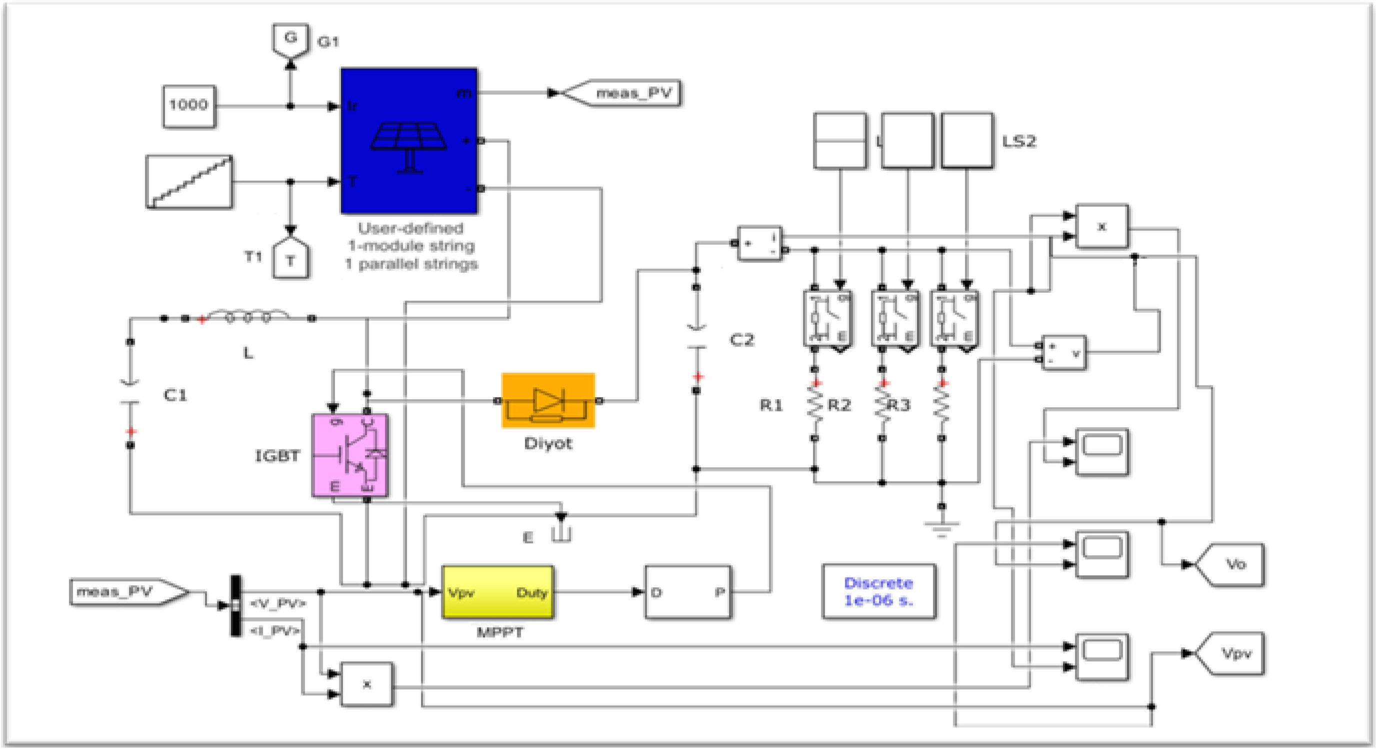

Fig. 3. MATLAB/Simulink model of the PV system to which the PSO algorithm is applied.

First of all, by integrating the PSO algorithm into the MPPT process, it has been observed that the system responds much faster in transient regimes compared to traditional methods. In tests conducted in scenarios involving sudden changes in radiation and temperature values, the algorithm was able to reach the new maximum power point of the system in a very short time; this situation has revealed the potential to optimize the performance of the system, especially in regions where environmental fluctuations such as cloud transitions or shading are frequently experienced. In steady-state analyses, it has been determined that the PSO-supported MPPT algorithm significantly reduces power oscillations. This situation has allowed the system to operate more stably and reliably, and the losses due to fluctuations in energy transmission have been prevented. This stable behavior of PSO, compared to the instability problems frequently encountered by classical MPPT algorithms, is attributed to the algorithm's effective use of both individual and ensemble memory. Table 3 Temperature and output power values for PSO algorithm

Table 3. Temperature and output power values for PSO algorithm

Temperature (°C)	Output Power (W)
0	233,10
10	233,22
15	230,12
20	229,31
25	228,67
30	227,21
35	226,80
40	225,32
45	224,01
50	223,66
55	223,40
60	223,17

Table 3 presents the output power values obtained by the PSO algorithm under varying temperature conditions. The results clearly indicate a gradual decrease in output power as the temperature increases. This trend is a well-known characteristic of photovoltaic panels, where elevated cell temperatures lead to voltage drops, consequently reducing the overall power output. Despite these temperature-induced losses, the PSO algorithm demonstrated its ability to consistently track the MPP, maintaining efficient system operation. These findings confirm the robustness and reliability of the PSO-based MPPT method under thermal variations, highlighting its practical advantage, particularly in regions subject to frequent temperature fluctuations.

4.1. Dynamic performance

A +10 °C step applied at 25 °C produced a transient settling time of < 20 ms and a steady-state power ripple of 0.7 %. These values confirm the fast convergence and low oscillation capability of the proposed PSO algorithm.

Table 4. Performance comparison of PSO-based MPPT studies.

Reference	Test focus	Key result	η_MPPT / ripple
Rakhmatov et al. [31]	Variable irradiance	97 % efficiency	—
Sera & Teodorescu [36]	Low irradiance	< 2 % ripple	95 %
This work	0–60 °C sweep	t_settle < 20 ms, 0.7 % ripple	90.2 %

The performance comparison in Table 4 clearly demonstrates the strengths of the proposed PSO-based MPPT method, particularly under thermally dynamic conditions. Unlike earlier studies that primarily focused on irradiance variation, this work emphasizes temperature adaptability, which is often overlooked yet critical for real-world PV deployments. The rapid settling time and minimal steady-state power ripple observed confirm the algorithm's ability to swiftly adapt to thermal disturbances while preserving tracking accuracy. These results are indicative of an optimized control structure capable of maintaining system stability even in the face of rapid parameter fluctuations. Furthermore, the algorithm's performance across the entire temperature sweep suggests a high level of robustness, making it suitable for environments with frequent and unpredictable climate changes. This reinforces the practical viability of the method for geographically diverse PV installations, where thermal gradients are as impactful as solar intensity variations. Table 5 shows literature information.

Table 5. Literature studies

Reference	Key Focus	Main Findings / Contributions	Efficiency Improvement
Rakhmatov et al. [31]	PSO - Classical MPPT Comparison	Fast, accurate MPPT; reduced losses.	Accurate, fast tracking.
Esram and Chapman [32]	MPPT Techniques Comparison	Low oscillation, high accuracy.	Stable, precise tracking.
Gaafar et al. [33]	PSO - Weather Conditions Effect	High adaptability.	Adaptation to change.
Kumari and Babu [34]	Hybrid PSO-INC	Stable power, reduced losses.	Loss reduction.
Kumar and Manoharan [35]	Hybrid PSO-Fuzzy Logic	High accuracy, stability	Accurate tracking.
Sera and Teodorescu [36]	PSO - Low Irradiance	High performance.	Gain in low light.
Abdelsalam et al. [37]	PSO - Processing Time	Fast implementation.	Real-time efficiency.
Benhmed et al. [38]	PSO - Maxima Separation	High long-term efficiency.	Global maximum finding.
Nacer et al. [39]	PSO - FPGA Implementation	Fast computation.	Speed in hardware.
Liserre et al. [40]	PSO - High Power	Low loss, high efficiency.	Gain in large systems.
Femia et al. [41]	PSO - Stability	Balanced power.	System resilience.
Boukenoui et al. [42]	PSO - Hybrid Systems	High energy production.	Resource optimization.
Jena et al. [43]	Adaptive PSO	Fast response.	Adaptation to environmental
Lian et al. [44]	PSO Parameters	Correct tuning is important.	Parameter optimization.
Rezk and Eltamaly [45]	Hybrid PSO-ANN	Accurate prediction, high efficiency.	Efficiency with prediction.

This study contributes to the ongoing research on MPPT techniques for photovoltaic systems by presenting a novel implementation of the PSO algorithm. While previous works have demonstrated the general effectiveness of PSO in MPPT applications, this research further refines the PSO-based MPPT approach by:

Providing a detailed analysis of the algorithm's performance under a wider range of dynamic environmental conditions, specifically focusing on the simultaneous impact of rapid irradiance and temperature fluctuations. Introducing a modified parameter adaptation strategy that enhances the algorithm's convergence speed and reduces steady-state oscillations, thereby improving overall energy extraction efficiency. Developing a MATLAB/Simulink model that incorporates a comprehensive representation of the PV system's electrical characteristics, enabling a more accurate evaluation of the MPPT algorithm's performance in real-world scenarios. The findings of this study offer valuable insights into optimizing PSO-based MPPT controllers for enhanced performance and reliability in photovoltaic energy systems

5. Conclusions

In this study, an original approach has been developed based on the PSO algorithm to perform the MPPT function in PV. The developed PSO-based MPPT method has been extensively tested under different operating conditions in the PV system model created in the MATLAB/Simulink environment. A PSO-based MPPT controller was implemented and evaluated for a 250 W PV module under a fixed irradiance of 1000 W m^{-2} and a 0 °C–60 °C temperature sweep. The algorithm maintained an average tracking efficiency of 90.2 %, settled to the new MPP in < 20 ms, and limited steady-state power ripple to 0.7 %.

Especially in transient situations where sudden radiation and temperature changes are simulated, it has been observed that the PSO-based MPPT algorithm responds quickly and reaches the MPN in a shorter time. This supports the high ability of the algorithm to adapt to dynamic environmental conditions and its potential to maximize system efficiency. In addition, it has been determined that the PSO method provides a more stable power output by minimizing power oscillations in steady-state operation. This feature enables PV systems to be used reliably in various areas such as grid integration and independent power applications.

It is concluded that the developed PSO based MPPT method is an effective solution for improving critical performance parameters such as stability, speed and efficiency in energy production of photovoltaic systems. This study confirms the applicability and superior performance of the PSO algorithm in real-time MPPT applications of PV systems and makes a significant contribution to the technological developments in the field of renewable energy.

Although real-time implementation was not within the scope of this simulation-based study, we recognize its importance for practical deployment. Therefore, a suggested roadmap has been outlined, highlighting the necessary steps and technical considerations for a future FPGA or DSP-based real-time implementation of the proposed PSO MPPT algorithm. This also opens pathways for testing in grid-connected or hybrid PV systems with actual environmental variability.

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