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Research Article

Maximum Power Point Tracking and Efficiency Increase in Photovoltaic Systems with Particle Swarm Optimization

Parçacik Sürüsü Optimizasyonu ile Fotovoltaik Sistemlerde Maksimum Güç Noktasi Takibi ve Verimlilik Artışı

Abdil KARAKAN[*1], Yüksel OĞUZ[2], Nazlıcan GÜVENÇ[3]

[1] Afyon Kocatepe University Dazkırı Vocational School Electrical Department;
[2] Afyon Kocatepe University, Faculty of Technology, Electrical and Electronics Engineering;
[3] Afyon Kocatepe University, Faculty of Technology, Electrical and Electronics Engineering;
[*] Corresponding Author; akarkan@aku.edu.tr

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ABSTRACT

In line with the growing global energy demand and environmental sustainability goals, interest in renewable energy sources has been increasing rapidly. Among these sources, photovoltaic (PV) systems have emerged as a significant alternative due to their ability to generate electricity directly from solar energy and their environmentally friendly nature. However, the output power of photovoltaic panels fluctuates continuously depending on factors such as solar irradiance, ambient temperature, and load conditions, which in turn leads to variations in system efficiency. Therefore, operating the system at the Maximum Power Point (MPP) at all times is essential for optimizing total energy production. In this study, a Particle Swarm Optimization (PSO)-based Maximum Power Point Tracking (MPPT) algorithm is proposed to accurately, rapidly, and stably track the maximum power point in photovoltaic systems. PSO, a nature-inspired metaheuristic algorithm, offers higher tracking accuracy, faster response time, and improved stability compared to conventional MPPT techniques. Simulation studies conducted in the MATLAB/Simulink environment demonstrate that the PSO-based approach performs effectively under varying environmental conditions and significantly enhances the energy efficiency of photovoltaic systems. The results indicate that the PSO algorithm can adapt to the dynamic characteristics of PV systems and serves as an efficient solution for real-time tracking applications.

Keywords: Photovoltaic Systems; Maximum Power Point Tracking; Particle Swarm Optimization; Renewable Energy; Energy Efficiency

ÖZET

Artan küresel enerji talebi ve çevresel sürdürülebilirlik hedefleri doğrultusunda yenilenebilir enerji kaynaklarına olan ilgi hızla artmaktadır. Bu kaynaklar arasında fotovoltaik (FV) sistemler, doğrudan güneş enerjisinden elektrik üretme kabiliyetleri ve çevre dostu yapıları nedeniyle önemli bir alternatif olarak ortaya çıkmıştır. Ancak, fotovoltaik panellerin çıkış gücü, güneş ışınımı, ortam sıcaklığı ve yük koşulları gibi faktörlere bağlı olarak sürekli dalgalanmakta ve bu da sistem verimliliğinde değişikliklere yol açmaktadır. Bu nedenle, toplam enerji üretimini optimize etmek için sistemi her zaman Maksimum Güç Noktası'nda (MPP) çalıştırmak esastır. Bu çalışmada, fotovoltaik sistemlerde maksimum güç noktasını doğru, hızlı ve kararlı bir şekilde izlemek için Parçacık Sürüsü Optimizasyonu (PSO) tabanlı bir Maksimum Güç Noktası Takibi (MPPT) algoritması önerilmiştir. Doğadan ilham alan meta-sezgisel bir algoritma olan PSO, geleneksel MPPT tekniklerine kıyasla daha yüksek takip doğruluğu, daha hızlı tepki süresi ve iyileştirilmiş kararlılık sunmaktadır. MATLAB/Simulink ortamında yürütülen simülasyon çalışmaları, PSO tabanlı yaklaşımın değişen çevre koşullarında etkili bir performans gösterdiğini ve fotovoltaik sistemlerin enerji verimliliğini önemli ölçüde artırdığını göstermektedir. Sonuçlar, PSO algoritmasının PV sistemlerinin dinamik özelliklerine uyum sağlayabildiğini ve gerçek zamanlı izleme uygulamaları için verimli bir çözüm sunduğunu göstermektedir.

Anahtar Kelimeler: Fotovoltaik Sistemler; Maksimum Güç Noktası Takibi; Parçacık Sürüsü Optimizasyonu; Yenilenebilir Enerji; Enerji Verimliliği

1. INTRODUCTION

In recent years, the increasing energy demand worldwide has rapidly increased the interest in alternative energy sources due to the limited and polluting properties of fossil fuels. In this context, renewable energy sources are of great importance for achieving environmental sustainability goals. Solar energy is one of the renewable energy sources that offer the most potential as a source that directly converts sunlight into electricity. Photovoltaic (PV) systems are of great importance as systems that directly convert sunlight into electrical energy and provide environmentally friendly energy production. Photovoltaic systems are rapidly spreading around the world thanks to increasing efficiency, decreasing costs and developing technology. However, the efficiency of photovoltaic systems varies depending on dynamic factors such as environmental factors, radiation, and temperature and load conditions. Therefore, photovoltaic systems must be operated continuously at the maximum power point (MPP) in order to operate efficiently. The output power of photovoltaic panels fluctuates constantly depending on environmental conditions. Factors such as changes in solar radiation, ambient temperature and load conditions cause the maximum power point of the system to shift. For this reason, Maximum Power Point Tracking (MPPT) algorithms are needed to increase the efficiency of photovoltaic systems. MPPT algorithms optimize the output power according to the instantaneous conditions of the system and ensure operation at the maximum power point. Although traditional MPPT methods have been developed to increase the performance of photovoltaic systems, most of these methods are insensitive to sudden changes in environmental conditions and sometimes create instability in the system (Esram and Chapman, 2007). Therefore, more flexible and advanced algorithms are required to track the optimum power point in photovoltaic systems quickly and accurately.

In recent years, considering the limitations of traditional MPPT methods, it has been observed that metaheuristic algorithms provide more effective solutions in photovoltaic systems. Particle Swarm Optimization (PSO), as an optimization technique inspired by nature, stands out as a promising method for MPPT applications in photovoltaic systems. PSO rapidly navigates in the solution space by imitating the collective movements of fish schools and bird groups and moves towards the optimum solution (Kennedy and Eberhart, 1995). These features make PSO an ideal choice for effective tracking of the maximum power point in photovoltaic systems. There are several important studies where PSO has been used successfully. Jordehi and Jovanovic demonstrated the ability of PSO to reach the maximum power point rapidly in photovoltaic systems, and better results were obtained compared to traditional methods. PSO ensures stable operation of the system even in sudden irradiance changes, which is a great advantage over traditional methods (Jordehi and Jovanovic, 2013). The performance of PSO in photovoltaic systems has also been confirmed by studies conducted under different environmental conditions stated that PSO exhibits lower oscillation under variable irradiance and temperature conditions and has the capacity to reach the maximum power point faster (Femia et al., 2005). This superior performance of PSO has been an important factor that increases the efficiency of photovoltaic systems. It shows that the PSO algorithm overcomes the limitations encountered by traditional MPPT methods and provides stable operation of the system with high accuracy (Jordehi, 2015). In addition, the ability of PSO to reach the global optimum optimizes the performance of photovoltaic systems by providing higher energy efficiency in the system. The PSO algorithm has a faster convergence time compared to other metaheuristic algorithms used in photovoltaic systems. This feature makes PSO a suitable solution for real-time applications of photovoltaic energy systems (Gonzalez et al., 2014). However, the adaptive properties of PSO allow the system to quickly adapt to changing environmental conditions, which ensures that the system always operates at maximum power point (Hussain and Asghar, 2017). Applications of PSO in photovoltaic systems have great potential in terms of efficiency increase and power optimization. In this study, a PSO-based MPPT algorithm is proposed for tracking the maximum power point in photovoltaic systems. This algorithm provides faster and more stable results compared to traditional methods. Simulations performed in the MATLAB/Simulink environment revealed that the PSO-based MPPT algorithm performed better in different irradiance and temperature scenarios. In addition, it was observed that PSO increased the efficiency of photovoltaic systems with low oscillation, fast response time and high accuracy. This study emphasizes that the PSO algorithm provides an effective method for optimizing the efficiency of photovoltaic systems and suggests a potential solution for future research.

2. MATERIALS AND METHODS

In this study, a Particle Swarm Optimization (PSO) based algorithm has been developed for tracking the maximum power point in photovoltaic (PV) systems and the effectiveness of this algorithm has been evaluated through simulations performed in MATLAB/Simulink environment. Photovoltaic panels, power converter elements (boost converter), voltage-current monitoring systems and control blocks including MPPT algorithm have been used as the basic components in the modelling process. Energy storage units have not been included in the simulation structure, therefore battery systems and charge control circuits have been excluded from the scope. PSO algorithm calculates the optimum duty cycle (D) value using instantaneous voltage (Vpv) and current (Ipv) data obtained from the PV panel and drives the IGBT switch by generating a PWM signal in line with this value. In order to ensure that the system operates at the maximum power point, the algorithm continuously analyzes the output power (P=V×I) and performs an iterative search to maximize the output power by updating the global best (gbest) solution. The PV panel model used has a power capacity of 250 W, a maximum power voltage of 30.7 V and a maximum power current of 8.15A, and the system performance was tested at different irradiance (200–1 000 W/m²) and temperature (0–75 °C) ranges. The performance of the MPPT algorithm under dynamic conditions was comparatively evaluated using the obtained I-V and P-V characteristic curves. The output voltage, current and power of the system were monitored at each step of the simulation; in particular, the transient behaviour, the time it took for the system to reach equilibrium and the amount of oscillation were analysed in detail. The PSO algorithm determined the optimum operating point quickly and decisively according to the panel characteristics, minimizing power oscillations. Thanks to the modular structure of the model, the adaptation of the PSO to different environmental conditions was facilitated and the potential of the algorithm in real-time applications was demonstrated.

2.1 Photovoltaic Systems

Photovoltaic (PV) systems are energy production systems consisting of semiconductor materials that can directly convert the radiation energy coming from the sun into electrical energy. In these systems, a transformation that does not require any mechanical movement and completely converts light energy into electrical energy takes place. In this respect, PV systems have advantages such as silent operation, low maintenance and long life. In the literature, these systems are often referred to as "solar cells" or "solar cells" (Benyoucef and Benbouzid, 2010).

The term "photovoltaic" is formed by combining two different words: "photo" is of Greek origin and means "light", while the term "voltaic" is related to the electrical potential difference and is derived from the surname of the Italian scientist Alessandro Volta. The combination of these two terms gave rise to the concept of "photovoltaic", which refers to the conversion of light into electrical energy (Duffie and Beckman, 2013).

This transformation, known as the photovoltaic effect, was first discovered experimentally in 1839 by the French physicist Alexandre Edmond Becquerel. Becquerel observed that when light was shed on an electrolyte solution containing electrodes, an electrical potential difference was created between these two electrodes, and thus demonstrated for the first time that light could be used to produce electrical energy (Kalogirou, 2009).

Today, widely used PV cells are usually produced in square, rectangular or circular shapes. The most preferred cell type on the market is silicon-based solar cells. The typical surface area of these cells is approximately 100 cm² and their thickness varies between 0.2 and 0.4 mm. The energy conversion efficiency of photovoltaic cells can vary greatly depending on the production technology and the type of semiconductor material used. Considering the current technologies, the highest conversion efficiency achieved in laboratory environments can reach up to 70%. However, this value generally varies between 15% and 22% in commercially used cells (Green et al., 2015).

In order to increase the electrical power generation capacity, individual solar cells are converted into larger structures by connecting them in series and/or parallel. Each of these structures is called a photovoltaic module. Photovoltaic panels are formed by combining multiple modules, and PV arrays are formed by connecting the panels in appropriate combinations. These arrays form the basis of systems that provide large-scale energy production. This hierarchical structure from the PV cell to the arrays makes it possible to optimize the output power of the system and produce more electricity in certain areas. Figure 1 shows the cell, module, panel and array.

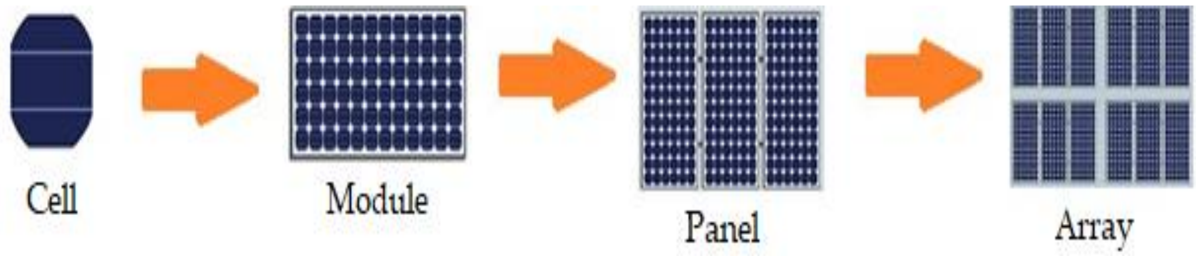

Figure 1. Cell, Module, Panel and Array.

The smallest component that forms the basic building block of photovoltaic systems is solar cells. These cells are produced from semiconductor materials that have the ability to directly convert light energy into electrical energy. These semiconductor materials have physical properties that enable the excitation of electrons under light and thus the generation of electric current. The main semiconductor materials that are widely preferred in solar cell production include crystalline silicon (Si), amorphous silicon (a-Si), cadmium telluride (CdTe), copper-indium-selenide (CIS) and copper-indium-gallium-selenide (CIGS). One of the most important criteria when selecting these materials is the conversion efficiency. Efficiency indicates how much of the light energy falling on the solar cell can be converted into electrical energy. Measurements made in laboratory environments show that crystalline silicon cells can provide an efficiency of up to approximately 25%. While this rate is approximately 22% in cells produced with thin film technology, similar efficiency values have been achieved in other newly developed cell technologies. These ratios vary depending on the structural properties of the cell, the type of material used and the production technique (Zhang and Chen, 2016).

In order for solar cells to become functional, a certain amount of additives are added to semiconductor materials to increase their electrical conductivity. This process is called doping. Thanks to the doping process, the semiconductor material gains electrical characteristics as "n-type" (negative) or "p-type" (positive). These types are the basic classifications that determine the type of conductivity and the majority carrier.

For example, to make a silicon-based material n-type, elements such as phosphorus, which are in group 5 of the periodic table, are preferred. The phosphorus atom has five electrons in its outer orbit and this extra electron is freed when integrated into the silicon crystal structure. Thus, these free electrons increase conductivity. The structures formed with this type of doping are called "donor" or "n-type" doping conductors.

Similarly, elements in group 3 of the periodic table are used to obtain a p-type semiconductor structure. Elements such as aluminium, boron and indium have three electrons in their outer orbits. When these elements are incorporated into the silicon crystal, an electron deficiency occurs. This deficiency is called a "hole" and is assumed to carry a positive charge. Therefore, such dopants are defined as "acceptor" or "p-type" dopants.

When n-type and p-type semiconductors are brought together in a suitable way, a junction is formed between them. This structure is called a p-n junction. In the junction region, the free electrons in the n-type semiconductor pass to the p-type region; while the holes in the p-type tend to pass to the n-type. This carrier transition occurs depending on the density difference of the carriers and after a while the movement of the carriers stops and a charge balance is formed in the system.

As a result of this transition, there are no free carriers in the junction region and this region is called the "depletion region" (transition region). This region causes negative charges to accumulate on the p side and positive charges on the n side. The resulting charge distribution creates an internal electric field in the region. This internal electric field ensures that the charge carriers (electron-hole pairs) formed during the operation of the structure under light are separated and directed. Photovoltaic conversion basically takes place in two stages. In the first stage, sunlight hits the semiconductor material and creates electron-hole pairs with the energy of the photons. In the second stage, these pairs are separated from each other by the effect of the structural electric field in the junction region and directed in a way that will contribute to the circuit. Thus, electric current is obtained through the external circuit. The internal structure of a solar panel cell is shown in Figure 2.

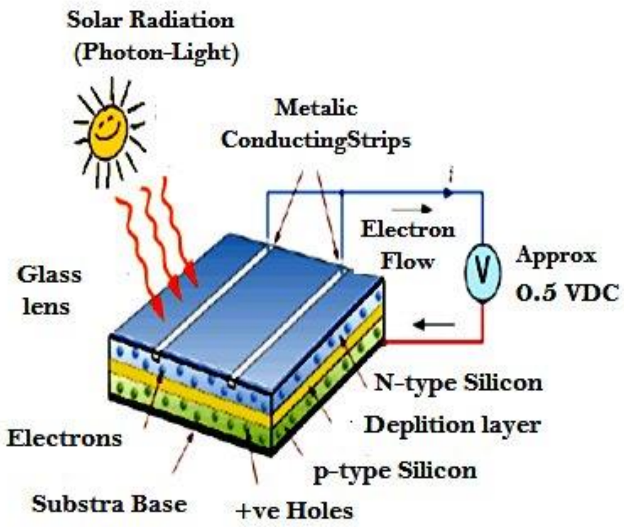

Figure 2. Internal structure of solar panel.

2.2. Classification of Solar Panel Systems

Photovoltaic energy systems are divided into three main classes according to their grid connection status: grid-connected (on-grid), grid-independent (off-grid) and hybrid systems. This classification varies according to the intended use of the systems, installation location, cost and technical requirements (IEA PVPS, 2020). Grid-integrated systems are generally preferred in urban residential and commercial buildings and transfer the electrical energy generated by the panels directly to the public grid. There is generally no energy storage unit in these systems; while excess energy is sold to the grid, the energy deficit is met from the grid. This provides advantages in terms of net metering and renewable energy incentives (Luthander et al., 2015). In contrast, off-grid systems are completely independent and operate without being connected to any central grid. Such systems are widely used in rural areas, mountainous regions or places where infrastructure services are limited. They play a critical role in regions where energy outages may occur. The use of batteries is mandatory in these systems; because if the production and consumption times do not match, energy is stored and kept for later use. Hybrid systems can both work connected to the grid and have energy storage capacity. These systems are generally applied in hospitals, data centers and similar structures where energy continuity is critical. In addition to solar energy, a hybrid structure is created by supporting it with wind turbines or diesel generators (Carpenter et al., 2012). The importance of hybrid systems is increasing, especially in developing countries where energy supply security is important.

2.3. Environmental and Technical Factors Determining the Efficiency of Solar Panels

The energy production capacity of photovoltaic panels is affected not only by the technological features of the panel itself, but also by the installation environment, maintenance conditions and climatic factors. These factors affecting the performance of PV systems are generally divided into two main groups: environmental and technical.

Environmental factors include the amount of solar radiation, atmospheric conditions, temperature changes, dust and shading. The intensity and duration of solar radiation directly determine energy production. For example, PV systems can operate with very high efficiency in regions with an annual average insolation potential of 1.800 kWh/m². Dust, pollen, bird droppings and other pollutants that cause a decrease in the light reaching the panel surface should be carefully monitored, especially in densely populated industrial areas (Adinoyi and Said, 2013). Temperature has a negative effect on the efficiency of PV cells. As the panel surface temperature increases, the band gap in the semiconductor cells changes and electricity production decreases. For this reason, natural or active ventilation solutions should be preferred in systems to be installed in high temperature regions. When looking at technical factors; panel type, production technology, aging process, mounting angle, connection type and electrical losses come to the fore. While monocrystalline silicon panels stand out with their high efficiency values, polycrystalline panels are more advantageous in terms of cost. Although thin film technology provides a performance advantage in low light conditions, general efficiency levels are lower (Green et al., 2015). In addition, thermal stress, humidity and UV rays that the system is exposed to over time can cause microscopic damage to the cell structure and cause performance degradation in the long term. For this reason, it is of great importance to monitor the systems at regular intervals, evaluate inverter performances and perform periodic maintenance activities (Jordan and Kurtz, 2013).

2.4. Maximum Power Point

Among the technologies developed to increase the efficiency of photovoltaic (PV) systems, maximize the electricity production obtained from solar energy and make energy conversion processes more effective, the concept of Maximum Power Point (MPP) plays a central role. PV panels produce a certain current (I) and voltage (V) when they interact with solar radiation. The power obtained by multiplying these values (P = V x I) represents the current production capacity of the system. However, this value is not constant under all radiation and temperature conditions; different environmental factors directly affect the performance of the system. The maximum electrical power that a solar panel can produce occurs at a certain point, that is, at a certain current-voltage combination. This special point is called the maximum power point (MPP) (Esram and Chapman, 2007).

The performance characteristics of PV systems are analysed through current-voltage (I-V) and power-voltage (P-V) curves. These curves are graphical representations of how the panel performs under constant irradiance and temperature. Only one point in these curves provides the condition where the power value is maximum. This point represents the optimum load point where the solar panel can operate most efficiently under certain environmental conditions. In order to obtain high efficiency from the PV system, the system must be operated at this point in real time (Hohm and Ropp, 2003). If the system deviates from this point, the amount of energy produced decreases, which leads to economic losses.

The most common technological solution developed to prevent this situation is Maximum Power Point Tracking methods. MPPT includes control algorithms that aim to reach and maintain the maximum power point at any time by continuously monitoring and analysing the operating point of PV systems. Thanks to these algorithms, the performance of the system is made independent of environmental changes and energy production is optimized (Femia et al., 2005). The maximum power point is not a fixed value; it changes continuously due to external factors such as solar radiation intensity, ambient temperature, panel temperature, pollution, and shading. For example, with increasing radiation, the MPP point shifts to a higher voltage and current combination, while increasing temperature generally decreases the voltage and negatively affects the MPP. Therefore, while there is a loss of efficiency in systems with fixed output characteristics, MPP tracking systems prevent these losses. MPPT technologies play a critical role in increasing the efficiency of PV systems, especially in regions with variable climate conditions, where cloud cover is frequently experienced during the day, or where panel temperatures change rapidly.

MPPT algorithms are based on the calculation of power values by continuously measuring the panel voltage and current. As a result of these calculations, the difference between the current operating point of the system and the maximum power point is determined and the system is adjusted to minimize this difference. The most widely used MPPT algorithms today include Perturb and Observe (P&O), Incremental Conductance (IncCond), and fuzzy logic-based methods. Each of these algorithms has different advantages and disadvantages in terms of the dynamic response of the system, computational complexity, energy efficiency, and cost.

The P&O method in particular is widely preferred due to its easy applicability and low computational load. However, this method has disadvantages such as creating unstable oscillations around the MPP and missing the MPP in rapid radiation changes (Femia et al., 2005). The Incremental Conductance method was developed to solve this problem and is based on the derivative analysis of the MPP point and provides a more stable operation. In advanced systems, artificial intelligence-based MPPT methods such as fuzzy logic, genetic algorithms or artificial neural networks provide higher efficiency due to their ability to respond adaptively to environmental factors.

MPP tracking systems, especially in grid-integrated PV systems, work integrated with the inverter. In these systems, the inverter provides both DC-AC conversion and performs the MPP tracking function. On the other hand, in grid-independent systems, MPPT usually works with charge controllers and is used to optimize battery charging. The MPPT hardware and software architecture required by these two systems differ.

As a result, the Maximum Power Point and the tracking systems related to it directly affect the economic efficiency as well as the technical efficiency of photovoltaic energy systems. The correct design of these systems, the selection of appropriate algorithms and the ability to adapt to environmental conditions ensure the sustainable and efficient operation of PV systems. Especially considering the increasing energy demand and the transition to renewable energy, the role of MPPT technologies is becoming more and more important every day.

2.5. Particle Swarm Optimization

The Particle Swarm Optimization (PSO) algorithm is an intuitive and population-based optimization method inspired by the collective movement patterns in nature. This algorithm, which was first introduced to the literature by Kennedy and Eberhart in 1995, aims to find the most suitable point in the solution space by mathematically modelling the foraging behaviours of natural groups such as bird flocks or fish schools (Kennedy and Eberhart, 1995). The essence of PSO is the structure in which each solution candidate is defined as a "particle" and these particles search as a population (swarm) by benefiting from individual and collective experiences (Poli et al., 2007). In the PSO algorithm, each particle is represented as having a certain speed and position in a multi-dimensional solution space. As particles move in this space, they update their speed and therefore their positions by taking into account their previous best positions (pbest) and the best position in the swarm (gbest). This process allows particles to learn based on both their individual experiences and collective intelligence. This movement of particles brings them closer to the optimum solution of the problem over time (Engelbrecht, 2005). The application steps of the PSO algorithm can be summarized as follows: In the first stage, particles are randomly distributed and the initial speed and position of each are determined. In each iteration, the fitness values corresponding to the current positions of the particles are evaluated and the best position (pbest) of each particle according to its own past performance and the best position (gbest) within the swarm are updated. In the next stage, the new speed of the particle is determined according to these two reference points and the particle moves to the next position with this new speed. This cycle is repeated until a certain stopping criterion is met (Bansal et all., 2014). The main reasons for preferring PSO are its simple structure and the low number of parameters required. In this respect, it contains less complexity than other heuristic techniques such as genetic algorithms. In addition, the parallel nature of the PSO algorithm offers a time-saving advantage in large-scale problems. However, it sometimes carries the risk of getting stuck in local maxima in high-dimensional and multi-mode problems. For this reason, hybrid versions of PSO have been developed in some studies, increasing the ability to reach global optimum (Al-Rashidi and El-Hawary, 2009). Particle Swarm Optimization has a very wide range of applications from engineering to finance, from medicine to artificial intelligence. It is known to give very successful results especially in renewable energy systems, such as maximum power point tracking (MPPT) applications in photovoltaic systems. In photovoltaic systems, it is necessary to find the most suitable operating point from the current-voltage curve of the solar panel, which varies depending on the environmental conditions. At this point, PSO can determine the global maximum point faster and more decisively compared to classical tracking algorithms (Dursun and Kurak, 2016). In cases such as shading effects, more than one local maximum may occur in the panel characteristic curve. Under these conditions, classical methods may cause the system to be fixed at a local maximum point instead of the global maximum. Thanks to the particle-based structure of PSO, the entire solution space is effectively scanned and the optimum point can be successfully determined even in such problems (Mohanty et all., 2017). In practice, the algorithm is usually integrated with a DC-DC converter (e.g. boost converter) and used to adjust the duty ratio of the converter to transfer the output voltage of the PV panel to the PV (Yasko, 2018). It has been proven in many academic studies that PSO directly contributes to the efficiency increase in photovoltaic systems. Especially in real-time applications, the tracking accuracy of PSO, the response of the system to sudden environmental changes and low oscillation values make it a very advantageous option among the PV tracking methods (Meziane and El-Amine, 2021). In addition, it is seen that more powerful and flexible systems can be developed when the algorithm is used with hybrid structures (e.g. fuzzy logic or artificial neural networks).

2.6. Statistical Analysis

The Particle Swarm Optimization (PSO) algorithm used in this study is a stochastic optimization method; therefore, it does not necessarily yield identical results in every execution due to its random initialization of particles. To ensure the statistical reliability and consistency of the obtained maximum power point tracking (MPPT) performance, the PSO algorithm was executed 30 independent times under identical simulation conditions. For each run, the maximum output power Pmax achieved by the photovoltaic (PV) system was recorded.

After 30 runs, the statistical indicators including Best, Mean, Minimum, and Standard Deviation (Std) values were calculated according to the following equations:

$$Pmean = \frac{1}{N}\sum_{i=1}^{N} Pi_{max} \tag{1}$$

$$Pmin = minPi_{max} \tag{2}$$

$$Pstd = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(Pi_{max} - Pmean)^2} \tag{3}$$

The results presented in Table 1 show that the PSO algorithm consistently converged to near-optimal solutions with very small variations between runs. The low standard deviation indicates that the proposed PSO-based MPPT controller provides stable, repeatable, and accurate tracking of the global maximum power point under varying operating conditions.

Table 1. Statistical Results of 30 Independent PSO Runs.

Run Count	Best Power (W)	Mean Power (W)	Min Power (W)	Std(W)
30	250.15	249.42	248.76	0.38

Simulation conditions: irradiance = 1000 W/m², temperature = 25 °C, PV array rated power = 250 W, duty cycle range = [0, 0.98].

As presented in Table 1, the PSO algorithm exhibited a high degree of consistency across 30 independent simulations. The best power value obtained was 250.15 W, which is very close to the theoretical maximum of the PV system (250 W). The mean power value of 249.42 W and a low standard deviation of 0.38 W indicate that the PSO-based MPPT controller achieved stable convergence toward the global maximum power point in almost every run. The small difference between the best and minimum power values demonstrates the robustness and repeatability of the algorithm. These findings confirm that the PSO method provides fast, accurate, and reliable tracking performance under identical operating conditions, making it an effective approach for real-time MPPT control in photovoltaic systems.

3. RESULTS AND DISCUSSION

Photovoltaic (PV) systems are structures that convert solar energy directly into electrical energy, and these systems consist of various components that work in harmony with each other. Each component plays a critical role in the overall efficiency of the system, energy management, power conversion capacity, and long-term durability. The healthy and effective operation of PV systems is possible by selecting the components correctly and working in harmony with the system in an integrated manner. Although there are some differences depending on the application area and the scale of the system, photovoltaic systems generally have similar basic structures.

Based on the MATLAB Simulink model used in this study, PV system components can be classified under three main headings. Photovoltaic panels are the basic energy production units that convert sunlight directly into electrical energy. Power converters, especially boost converters, are electronic circuit elements that ensure the most efficient use of the energy obtained from the panels. Connection elements and mechanical structures consist of carrier structures, cables, and other auxiliary components that perform the physical assembly and electrical connections of the system.

There are no energy storage units in this Simulink-based model; therefore, battery systems and charge control circuits were excluded from the evaluation. Instead, MPPT algorithms and power electronic components were prioritized and focused on in the study. 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.

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

This panel modelling was implemented in the MATLAB environment, and radiation changes (G = 200 W/m² - 1 000 W/m²) and temperature changes (T = 0°C - 75°C) were tested.

I-V and P-V characteristic curves were analysed and the performance comparison of MPPT algorithms was made.

The PSO (Particle Swarm Optimization) algorithm used in this study was preferred to determine the maximum power point in photovoltaic systems. In the model developed in the MATLAB/Simulink environment, the voltage (Vpv) and current (Ipv) values of the system were given as input to the PSO algorithm; the algorithm calculates the optimum duty cycle (D) value according to these data and drives the IGBT switch, thus maximizing the output power of the PV system.

In the Simulink model seen in Figure 3, the PSO algorithm is integrated into the center of the system. The voltage and current values received from the photovoltaic panel are evaluated by the algorithm, the appropriate control signal is generated, and the system operates stably.

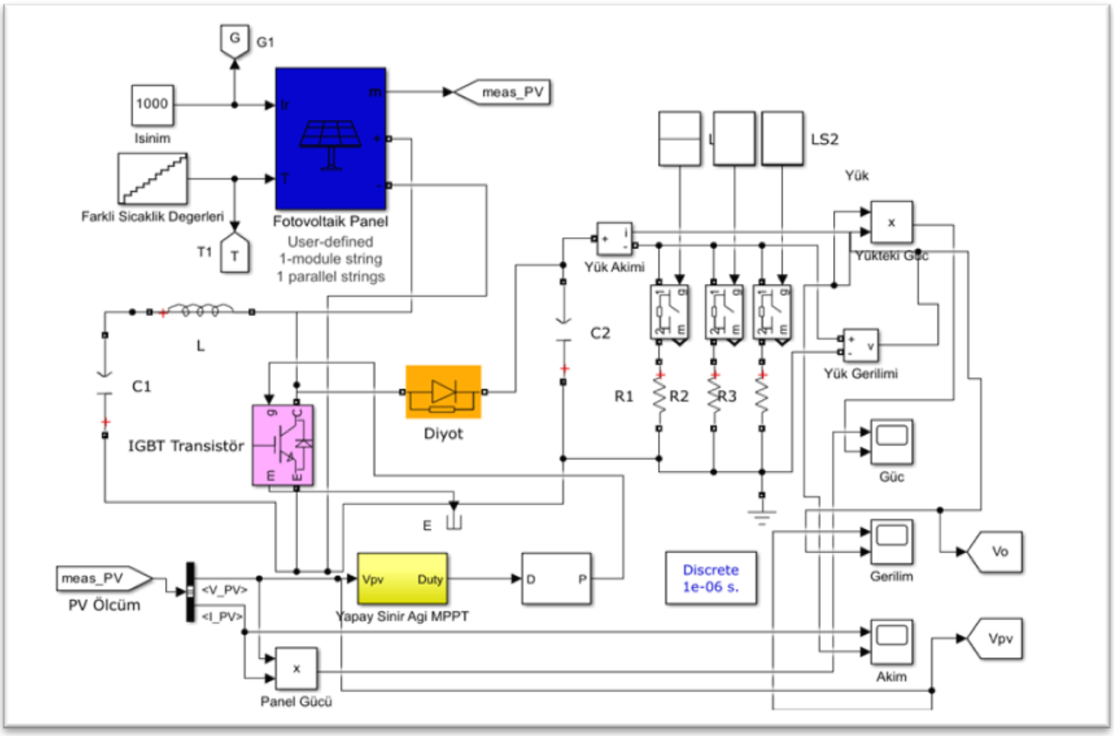

Figure 3. MATLAB/Simulink model of the PV system to which the PSO algorithm is applied.

As a result of the simulation, it was observed that the PV system operated with high efficiency and minimum oscillation under the PSO algorithm. Figure 4 shows how the output power of the system changes over time, and it is seen that the algorithm responds quickly to environmental variables. Figures 5 and 6 show the system current and voltage depending on time, respectively. The transient oscillations that occurred at the beginning were quickly suppressed.

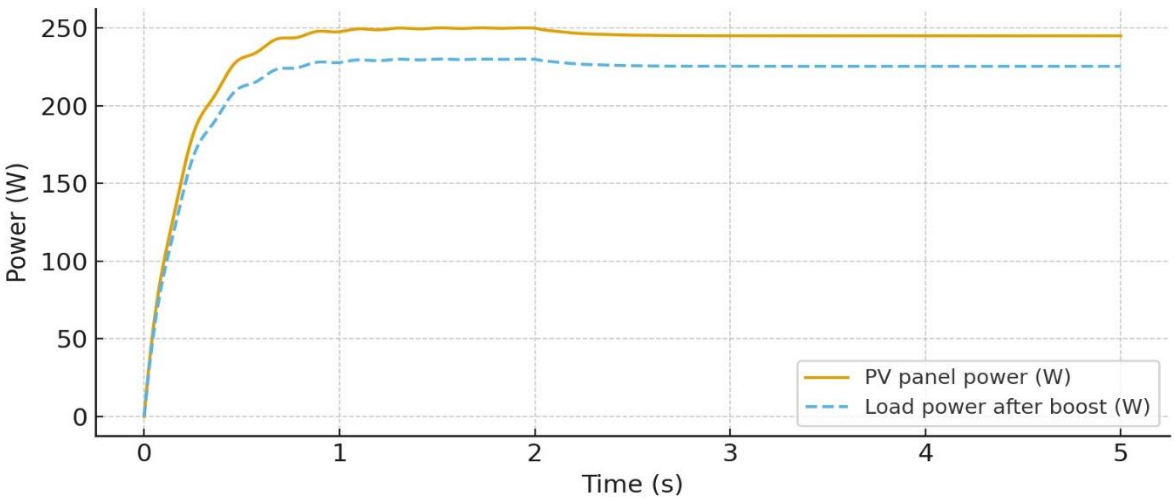

Figure 4. Change of output power obtained with PSO algorithm with respect to time.

In the graph, it is seen that the output power initially increases rapidly and stabilizes at around 230 W. This situation reveals the fast tracking capability of the PSO algorithm and its effectiveness in transient behaviour. There are two separate axes in the graph. The upper graph shows the power values directly produced by the PV panel, and the lower one shows the power values obtained on the load after the boost converter. This distinction is important to evaluate how efficiently the system works in line with the MPPT algorithm.

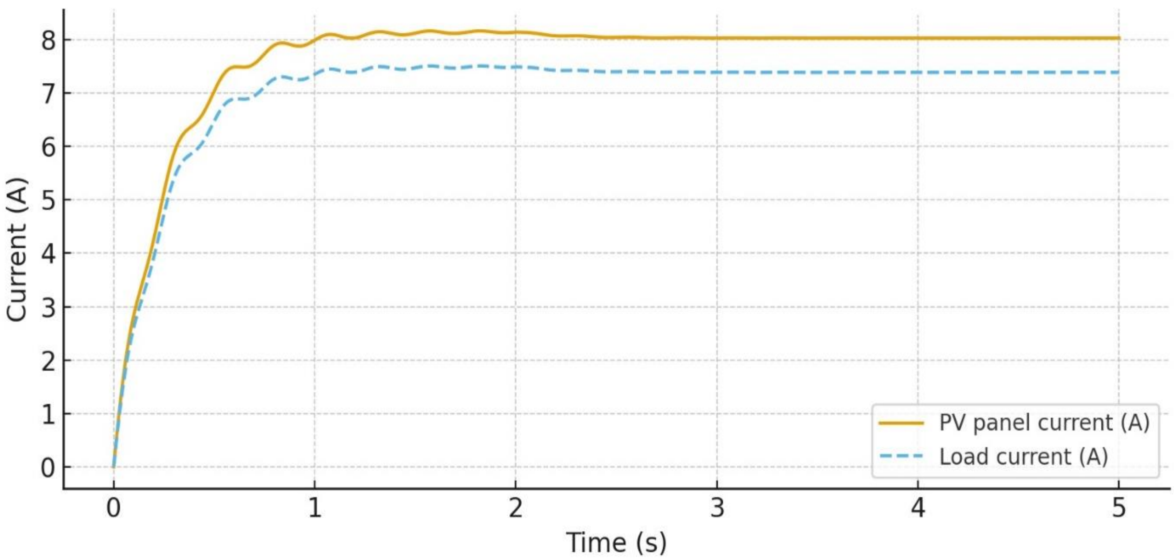

Figure 5. Current-time graph obtained with the PSO algorithm.

As seen in Figure 5, the system current shows short-term temporary oscillations against environmental changes, but it quickly stabilizes. This supports that the system operates stably at the maximum power point. The two-part structure in the graph represents the current value received from the PV panel on the top, and the output current measured on the load side on the bottom. This comparison reflects the real-time current regulation performance of the system.

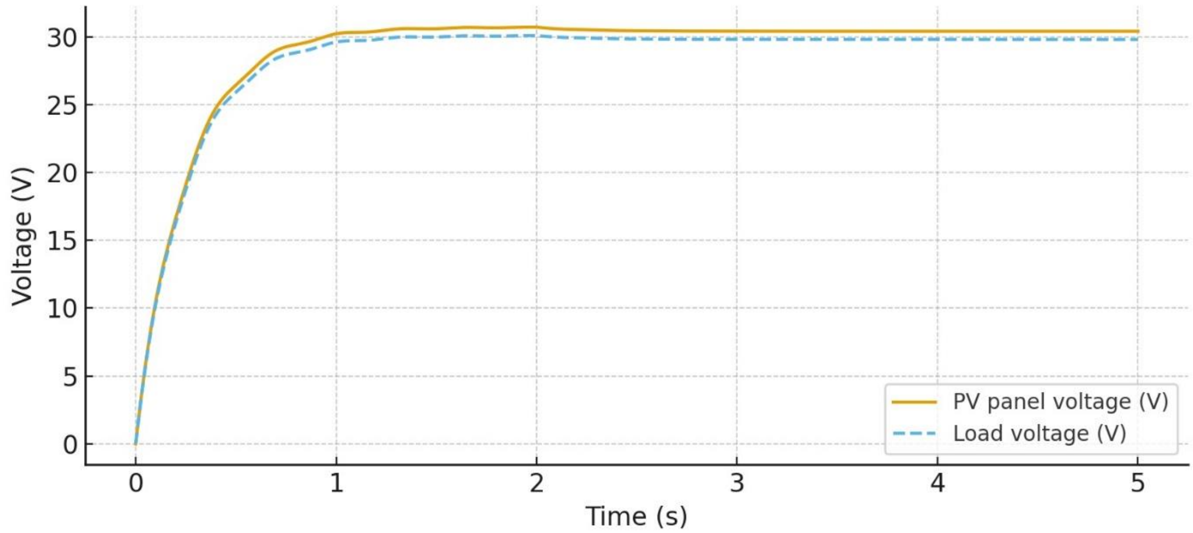

Figure 6. Voltage-time graph obtained with PSO algorithm.

In the voltage-time graph, an initial increase in voltage and then reaching a stable level is observed. This shows that the PSO algorithm stabilizes the system by determining the appropriate duty cycle.

4. CONCLUSIONS

The PSO algorithm has shown a very successful performance in terms of maximum power point tracking (MPPT) in photovoltaic (PV) systems. At the beginning of the simulation, that is, in the 0–1 second time interval under 0 °C temperature, the power output of the system reached from 0 W to approximately 250 W very quickly. This shows that PSO can detect the maximum power point in a very short time and operate the system efficiently and without oscillations.

After the first increase, the power output remained constant at approximately 250 W. This stability shows that the PSO algorithm minimizes oscillations and ensures that the PV system constantly produces maximum power. The fact that this stability is maintained despite the temperature change reveals that the algorithm is robust to environmental variables.

When the temperature increases to 10 °C in the simulation, a power loss of approximately 5 W is observed (from 250 W to 245 W). This decrease is a natural decrease due to the temperature coefficient of the PV panel. However, the PSO algorithm quickly adapted to this new situation and continued to keep the power level close to the maximum. When evaluated in terms of voltage, the system reached a stable voltage of approximately 30.7 V at 0 °C in a very short time. This clearly shows how fast and effective the PSO algorithm works in terms of MPPT control. This balance in voltage contributed to the stable operation of the system without fluctuations in power output.

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