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Performance of the rapid convergence time for the perturb and observe MPPT algorithm by using harris hawks optimization in photovoltaic systems

Fotovoltaik sistemlerde harris hawks optimizasyonu kullanılarak gözlem ve bozma MPPT algoritması için hızlı yakınsama süresinin performansı

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Performance of the Rapid Convergence Time for The Perturb and Observe MPPT Algorithm by Using Harris Hawks Optimization in Photovoltaic Systems

Highlights

- *Use hybrid P&O-HHO algorithm to accelerate convergence time*
- *Improve the overall tracking performance of the PV system*
- *Encompasses a boost converter for DC-DC power controlled by an MPPT algorithm*
- *Execution of a hybrid technique that combines Harris-Hawks Optimization*

Graphical Abstract

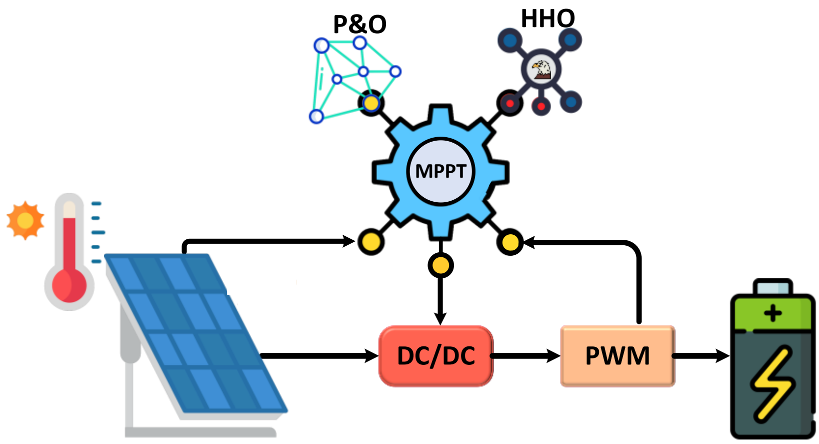

Figure. Graphical flowchart

Aim

The proposed hybrid P&O-HHO algorithm aims to accelerate convergence time and improve the overall tracking performance of the PV system.

Design & Methodology

To maximize power from PV modules at varying sun irradiance levels, Harris-Hawks Optimization (HHO) is offered as a performance improvement method for the conventional Perturb and Observe (P&O) approach in photovoltaic systems.

Originality

This study introduces an enhanced P&O algorithm by integrating it with Harris Hawks Optimization (HHO), a nature-inspired optimization technique known for its robust convergence characteristics.

Findings

The findings of the simulation illustrate that the HHO-P&O MPPT algorithm, as described, successfully identified the global maximum power point more efficiently.

Conclusion

the algorithm proposed has demonstrated notable efficacy and adaptability in accurately monitoring the maximum power point (MPP) across many scenarios.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Performance of the Rapid Convergence Time for The Perturb and Observe MPPT Algorithm by Using Harris Hawks Optimization in Photovoltaic Systems

Araştırma Makalesi / Research Article

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ABSTRACT

The efficiency of Maximum Power Point Tracking (MPPT) algorithms is crucial for optimizing the performance of photovoltaic (PV) systems. Traditional methods like the Perturb and Observe (P&O) algorithm are commonly used due to their simplicity, but they often suffer from issues such as slow convergence and oscillations around the maximum power point under changing environmental conditions. This study introduces an enhanced P&O algorithm by integrating it with Harris Hawks Optimization (HHO), a nature-inspired optimization technique known for its robust convergence characteristics. The proposed hybrid P&O-HHO algorithm aims to accelerate convergence time and improve the overall tracking performance of the PV system. To maximize power from PV modules at varying sun irradiance levels, Harris-Hawks Optimization (HHO) is offered as a performance improvement method for the conventional Perturb and Observe (P&O) approach in photovoltaic systems. The proposed model encompasses a boost converter for DC-DC power controlled by an MPPT algorithm, a PV panel, and a resistive load. The MPPT algorithm proposed is founded upon the execution of a hybrid technique that combines Harris-Hawks Optimization, a new method inspired by nature, and the conventional P&O approach. The suggested method has been tested through simulation testing utilizing the environment created by MATLAB Simulink. The findings of the simulation illustrate that the HHO-P&O MPPT algorithm, as described, successfully identified the global maximum power point more efficiently. Additionally, it exhibited a rapid convergence speed, superior outcomes in comparison to the standard Perturb and Observe method, and a swift dynamic reaction.

Keywords: Maximum Power Point Tracking, Harris-Hawks Optimization, Perturb and Observe, Photovoltaic.

Fotovoltaik Sistemlerde Harris Hawks Optimizasyonu Kullanılarak Gözlem ve Bozma MPPT Algoritması İçin Hızlı Yakınsama Süresinin Performansı

ÖZ

Maksimum Güç Noktası İzleme (MPPT) algoritmalarının verimliliği, fotovoltaik (PV) sistemlerin performansını optimize etmek için çok önemlidir. Perturb ve Observe (P&O) algoritması gibi geleneksel yöntemler, basitlikleri nedeniyle yaygın olarak kullanılır, ancak genellikle yavaş yakınsama ve değişen çevre koşulları altında maksimum güç noktası etrafında salınımlar gibi sorunlardan muzdariptirler. Bu çalışma, sağlam yakınsama özellikleriyle bilinen doğadan ilham alan bir optimizasyon tekniği olan Harris Hawks Optimizasyonu (HHO) ile entegre edilerek geliştirilmiş bir P&O algoritması sunmaktadır. Önerilen hibrit P&O-HHO algoritması, yakınsama süresini hızlandırmayı ve PV sisteminin genel izleme performansını iyileştirmeyi amaçlamaktadır. Değişen güneş ışınımı seviyelerinde PV modüllerinden gelen gücü en üst düzeye çıkarmak için, fotovoltaik sistemlerde geleneksel Perturb and Observe (P&O) yaklaşımı için bir performans iyileştirme yöntemi olarak Harris-Hawks Optimizasyonu (HHO) önerilmektedir. Önerilen model, bir MPPT algoritması, bir PV paneli ve bir dirençli yük tarafından kontrol edilen DC-DC gücü için bir yükseltme dönüştürücüsünü kapsar. Önerilen MPPT algoritması, doğadan ilham alan yeni bir yöntem olan Harris-Hawks Optimizasyonu ile geleneksel P&O yaklaşımını birleştiren hibrit bir tekniğin uygulanması üzerine kurulmuştur. Önerilen yöntem, MATLAB Simulink tarafından oluşturulan ortamdan yararlanılarak simülasyon testi yoluyla test edilmiştir. Simülasyonun bulguları, HHO-P&O MPPT algoritmasının, açıklandığı gibi, küresel maksimum güç noktasını daha verimli bir şekilde başarılı bir şekilde tanımladığını göstermektedir. Ek olarak, standart Perturb ile karşılaştırıldığında hızlı bir yakınsama hızı, üstün sonuçlar sergiledi ve Yöntemi ve hızlı dinamik reaksiyonu gözlemleyin.

Anahtar Kelimeler: Maksimum Güç Noktası Takibi, Harris-Hawks Optimizasyonu, Perturb and Observe, Fotovoltaik

1. INTRODUCTION

Photovoltaic (PV) systems have become a cornerstone of renewable energy solutions due to their ability to convert sunlight directly into electricity. The efficiency of these systems is critically dependent on the performance of Maximum Power Point Tracking (MPPT) algorithms, which ensure that the PV panels operate at their maximum power point (MPP) despite varying

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environmental conditions such as changes in solar irradiance and temperature. Among the various MPPT techniques, the Perturb and Observe (P&O) algorithm is widely used due to its simplicity and ease of implementation. However, the traditional P&O algorithm has notable drawbacks, including slow convergence to the MPP and significant oscillations around it, particularly under rapidly changing conditions [1][2]. Recently, the demand for electrical energy has increased, and the impact of its production, such as warming temperatures and pollutants, has also witnessed a rise. The search for alternative energy sources has therefore become a global effort. Many researchers are working on different ways to replace the normal fossil fuels of gas, oil and coal with renewable energy [3].

Solar power is regarded as one of the most prominent forms of clean and renewable energy sources. Its popularity is increasing due to advancements in solar panel production. Photovoltaic (PV) solar cells are widely utilized in the solar technology domain, predominantly due to their prevalence. These cells exhibit optimal performance in clear atmospheric conditions where few obstructions impede direct exposure to sunlight. Nevertheless, on certain occasions, the dependability of solar energy is compromised by partial barriers such as tree limbs or certain structures. The relationship between the current and voltage curves of solar panels is influenced by temperature and irradiance, which may be attributed to the photovoltaic characteristics of these panels [4][5].

The operating voltage of a PV array determines how much electricity it produces. The MPP of a PV system change depending on the temperature and sun irradiation levels. The maximum power is provided at a certain operating point that is specified by the I-P and V-P characteristic curves. The PV performs at peak efficiency at the MPP. For the photovoltaic panels to work at maximum power under different temperatures and irradiation levels, a boost converter controlled by the MPPT algorithm ought to be added between the solar panel and the load. As a consequence, the PV modules are compelled to function at their peak efficiency regardless of changing climatic circumstances [2][6]. The ideal current and voltage are tracked using several maximum power point tracking (MPPT) techniques that take environmental variations into account [7].

Among them are conventional methods like the directly estimated methodology (DEM), which calculates the ideal voltage depending on the current weather conditions (sunlight radiation and temperature) and utilizes the module characteristics and A precise representation of the photovoltaic array [8][9], and the FOCV (fractional open-circuit voltage), With an equally distributed amount of irradiance, the terminal voltage of the MPP will be almost constant in this manner. The ideal voltage of a photovoltaic (PV) array exhibits a direct relationship with the open-circuit voltage [10]. The hill climbing and P&O approaches are the most well-known traditional MPPT methods.

The primary distinction between these two methods is that hill climbing alters the DC-DC converter's duty cycle, and the duty cycle change is based on the power change. On the other hand, P&O implements a perturbation that affects the voltage at the terminals of the photovoltaic (PV) array [11]. Using the fact that the slope of the PV array's power-voltage curve at the MPP is zero, an incremental inductance (INC) method was proposed to improve tracking accuracy and dynamic behavior when conditions change quickly [12][13].

The modified method was proposed to make use of the PV modules' instantaneous changes in current and voltage. In contrast to the traditional incremental conductance algorithm, which bases its conclusion on the place of the MPP, the modified incremental inductance (INC) technique makes an assessment on the basis of the directions of power, voltage, and current [14][15].

However, these algorithms have some drawbacks. The accuracy of these algorithms can be increased in regards to shortcomings such as convergence speed and MPP-centered oscillations by using the soft-computing technique to adjust variable step sizes similar to those used with HC, INC, and P&O [16][17].

Most hybrid MPPT algorithms fall into this category of two-stage methods, where the traditional MPPT method is used to control the system after the soft computerization approach has been used to effectively capture the global power in a very rapid convergence, such as the one proposed to stop repeating failed solutions. The addition of the tabu list has changed the conventional bat algorithm. Additionally, IC has been used in the search strategy for quick monitoring in the event that MPP varies gradually [18]. Several global MPPT algorithms based on soft computing were introduced in [19], including hybrid MPPT techniques between artificial neural networks (ANNs) and P&O [20][3].

To address these limitations, this study proposes an enhanced version of the P&O algorithm by integrating it with the Harris Hawks Optimization (HHO) technique. HHO is a nature-inspired optimization algorithm based on the cooperative behavior and chasing strategy of Harris hawks in the wild. It is known for its fast convergence and ability to escape local optima, making it a suitable candidate for improving the performance of MPPT algorithms in PV systems.

The primary objective of this research is to evaluate the performance of the hybrid P&O-HHO algorithm in terms of convergence speed, stability, and overall tracking efficiency. By leveraging the adaptive and dynamic characteristics of HHO, the proposed method aims to mitigate the shortcomings of the conventional P&O algorithm, resulting in more efficient and reliable PV energy harvesting.

This work proposes a precise method for MPP tracking dependent on the HHO-P&O algorithm. This suggested algorithm's primary goal is to achieve speedy convergence while simultaneously boosting system efficiency. The major goal is to ensure quick MPP monitoring while retaining key performance metrics including accuracy, real-time MPP identification and tracking, tracking stability, and decreased algorithm complexity and computation time. The HHO algorithm is used for the choice of the delta-duty cycle (dD) suitable size and transitioned to the P&O method to calculate the duty cycle (D) in case of sudden changes in solar irradiation. After obtaining the MPP, the delta-duty cycle (dD) is constant in the P&O algorithm.

1.1. Contribution

While simple, traditional perturb and observe (P&O) algorithms struggle with slow convergence and oscillations around the maximum power point, especially under changing environmental conditions. This study is the introduction of an enhanced P&O algorithm for Maximum PowerPoint Tracking (MPPT) in photovoltaic systems by integrating it with the Harris Hawks Optimization (HHO) technique. HHO, a nature-inspired optimization algorithm, is used to enhance the performance of the traditional P&O method by helping it converge to the maximum power point faster and more accurately.

1.2. Organization

This paper is structured as follows: Section 2 provides a detailed overview of the PV System Design. Section 3 describes the methodology for integrating HHO with P&O and outlines the experimental setup. Section 4 presents the simulation and experimental results, highlighting the improvements in convergence time and tracking performance. Finally, Section 5 concludes the study with a discussion of the findings and potential future work in this area.

2. PV SYSTEM DESİGN

When developing and showcasing a detailed PV system, it is essential to carefully consider the following crucial elements:

- System Configuration: Define the setup of the PV system, including the quantity and layout of solar panels, inverters, batteries (if needed), and other essential components[21].
- Maximum Power Point Tracking (MPPT) Algorithm: Choose a suitable MPPT algorithm tailored to the system's specific demands. Evaluate various MPPT techniques like Perturb and Observe (P&O), hill climbing, and incremental inductance (INC), among others, weighing their pros and cons[22].
- Environmental Factors: Factor in environmental variables that can impact the PV system's performance, such as variations in solar irradiance, temperature fluctuations, shading effects, and potential obstructions [23], [24].
- Voltage and Current Characteristics: Grasp the interrelation between the current and voltage curves of solar panels, particularly how temperature and solar intensity influence these traits [25].
- Efficiency Optimization: Concentrate on enhancing the efficiency of the PV system by ensuring it consistently operates at its maximum power point (MPP) across diverse climatic conditions [26].
- MPPT Techniques: Delve into different MPPT methodologies like directly estimated methodology (DEM), fractional open-circuit voltage (FOCV), and others to effectively track the optimal current and voltage for peak power generation[27].
- Implementation of Boost Converter: Contemplate integrating a boost converter regulated by the MPPT algorithm between the solar panel and the load to maintain optimal efficiency regardless of changing weather conditions[28], [29].
- Design Considerations: Take into account design factors such as scalability, reliability, maintenance needs, and overall cost-effectiveness to ensure a well-rounded PV system plan[30].

3. THE PROPOSED ALGORİTHM

The Harris Hawks Optimization (HHO) algorithm is a nature-inspired metaheuristic optimization technique developed by mimicking the cooperative hunting behavior and dynamic chasing strategies of Harris hawks in the wild. This algorithm has gained attention due to its simplicity, flexibility, and effectiveness in solving complex optimization problems. HHO is particularly well-suited for applications requiring rapid convergence and robust performance across diverse search spaces. The efficacy of this algorithm depends on the incorporation of both exploratory and exploitative stages in order to effectively explore prey as shown in Figure 1. HHO has the potential to address various optimization problems effectively due to its population-based nature and lack of dependence on gradients. This transition is characterized by the energy level of the target, denoted as E. The energy is determined by Equation (1), and both the exploration and exploitation phases are subdivided into several stages according to the values of [q, E, r] [31].

$$E = 2E_O\left(1 - \frac{t}{T}\right) \tag{1}$$

Where E0 is the initial energy and T denotes the maximum number of repeats.

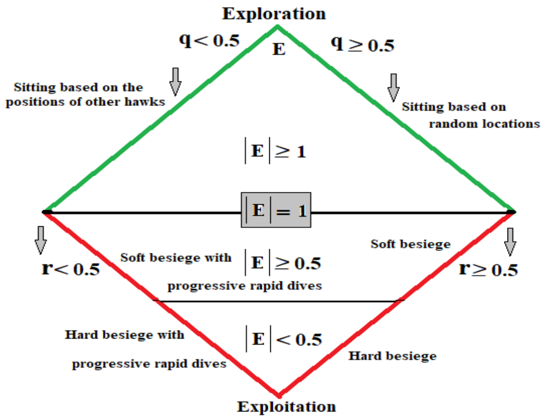


Figure 1. Behavior phases of HHO.

3.1. Exploration Stage

In the HHO algorithm, Hawks appear at random locations and begin waiting for a prey; typically, this action is carried out using one of two techniques. The first tactic is when the Harris' Hawks take up a position near other members of their family; this offers them a better chance to attack and capture the prey. In this technique, the distance between members of the hawks family is determined by the factor (q), which takes the value of q < 0.5.

The second standing technique is used when Harris Hawks stand in random places, such as very tall trees, but are still within a certain range, and the (q) factor is set to q ≥ 0.5. The following are the mathematical expressions for both standing techniques:

$$X(t+1) = \begin{cases} x_{rand}\,(t) - r_1|X_{rand}(T) - 2r_2X(t)| & q \geq 0.5 \\ (X_{rabbit} - X_m(t)) - r_3\,(lb + r_4(ub - lb)) & q < 0.5 \end{cases} \quad (2)$$

The variables (r1, r2, r3, r4, and q) represent a variety of numbers within 0 to 1. The variables (lb, ub) represent lower-upper limits of variables. X (t) is the instantaneous placement of the Hawks. The variable t represents the current repeats number. The variable (Xrand) represents a randomly generated position of the rabbit. The variable (Xrabbit) represents the instantaneous placement of the rabbit. N is number of Hawks. The variable (Xm) represents the average placement calculated using Eq. (3).

$$X_m(t) = \frac{1}{N}\sum_{i=1}^{N} X_i\,(t) \quad (3)$$

3.2 Exploitation Stage

This phase depends on the values of [E, r], which determine the status of the algorithm in any of the following four stages. The variable (r) is the chance of a prey in successfully escaping.

3.2.1 Soft besiege

The placement has been updated to a soft besiege state, as determined by the conditions and computed using Eq. (4).

$$X(t+1) = \Delta X(t) - E|JX_{rabbit}(t) - X(t)| \quad (4)$$

$$\Delta X(t) = X_{rabbit}(t) - X(t) \quad (5)$$

$$J = 2(1 - r_5) \quad (6)$$

The variable J represents the magnitude of the random leap made by the prey. (r5) is a numerical value that falls within the interval of 0 to 1.

3.2.2 Hard besiege

The HHO algorithm update it positions to the hard besiege, it is carried out to capture the rabbit. The choice is based on the distance between the rabbit and its energy, as in Eq. (7).

$$X(t+1) = X_{rabbit}(t) - E|\Delta X(t)| \quad (7)$$

3.2.3 Soft besiege with progressive rapid dives

The subsequent action taken by the hawks in the context of soft besiege is determined by the use of Eq. (8), while the implementation of progressive fast dives is carried out by the application of the leap scheme as described in Eq. (9).

$$Y = X_{rabbit}(t) - E|J * X_{rabbit}(t) - X(t)|$$

(8) $Z = Y + S \times LF(D)$

(9)

In this context, the dimension of the issue is denoted by D. The random vector S has a size of 1xD. LF represents the Levy flight function, which is computed using Equation (10).

$$LF(x) = \frac{0.01 * u * \sigma}{|v|^{\frac{1}{\beta}}} \quad (10)$$

And σ calculated by using Eq. (11).

$$\sigma = \left(\frac{\Gamma(1+\beta) * \sin\left(\frac{\pi\beta}{2}\right)}{\Gamma\left(\frac{1+\beta}{2}\right) * \beta * 2^{\frac{\beta-1}{2}}}\right)^{\frac{1}{\beta}} \quad (11)$$

Where β = 1.5, u and v are is a numerical value that falls within the interval of 0 to 1.

Eq. (12) concludes the method for updating the hawks' position.

$$X(t+1) = \begin{cases} Y & if \quad F(Y) < F(X(t)) \\ Z & if \quad F(Z) < F(X(t)) \end{cases} \quad (12)$$

3.2.4 Hard besiege with progressive rapid dives

In this stage, the energy of the prey decreases, the hawks are attacking the prey, and in a hard besiege condition, the following rule is implemented as in Eq. (13):

$$X(t+1) = \begin{cases} Y & if \quad F(Y) < F(X(t)) \\ Z & if \quad F(Z) < F(X(t)) \end{cases} \quad (13)$$

Where Y and Z are calculated as in Eq. (14) and Eq. (9).

$$Y = X_{rabbit}(t) - E|J * X_{rabbit}(t) - X_m(t)| \quad (14)$$

3.3 Proposed MPPT Algorithm

In the Proposed MPPT Algorithm, a comparison is drawn with the Conventional P&O Algorithm are depicted in Figure 2 [16], emphasizing its fundamental principles and modifications aimed at expediting convergence towards attaining the Maximum PowerPoint (MPP).

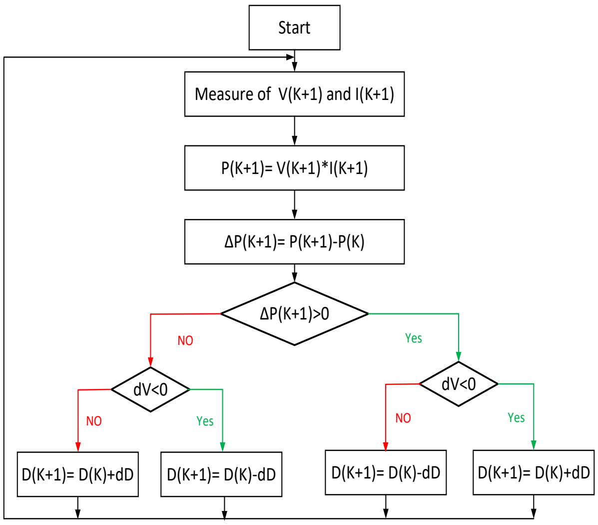


Figure 2. Flowchart of the conventional method

The innovative HHO-P&O algorithm is introduced, highlighting its fusion of P&O and Harris-Hawks methodologies to achieve optimal power point tracking. The flowchart of the HHO-P&O algorithm, depicted in Figure 3, elucidates how the HHO technique is leveraged to ascertain the ideal delta duty cycle value, subsequently utilized by the P&O technique for duty cycle computation. Through simulations conducted in MATLAB Simulink, the behavior of a photovoltaic panel is scrutinized under varied test scenarios, with a primary aim of optimizing MPP tracking while enhancing system efficiency and performance metrics.

In sum, the proposal showcases a meticulous and holistic approach to addressing MPPT in photovoltaic systems by integrating advanced optimization techniques and control algorithms.

The simulation results were executed by MATLAB Simulink to examine the behavior of a photovoltaic (PV) panel under two distinct test scenarios. The primary objective of the algorithm proposed is to get rapid convergence while simultaneously enhancing the efficiency of the system. The primary objective is to achieve efficient MPP tracking while simultaneously preserving the enhanced performance of crucial aspects, including MPP accuracy, real-time detection and tracking, tracking stability, algorithmic simplicity, and computational efficiency. The HHO method is employed to determine the optimal magnitude of the delta duty cycle (dD), which is subsequently utilized by the P&O algorithm to compute the D in response to abrupt variations in solar irradiation.

In the P&O technique, the delta duty cycle (dD) remains constant after the acquisition of the MPP and the control parameters in the proposed hybrid algorithm are described in table 1.

Table 1: Control Parameters of the proposed hybrid algorithm

The population size N	10
Maximum number of iterations T	10
Lower bounds lb	-0.7
Upper bounds ub	0.9

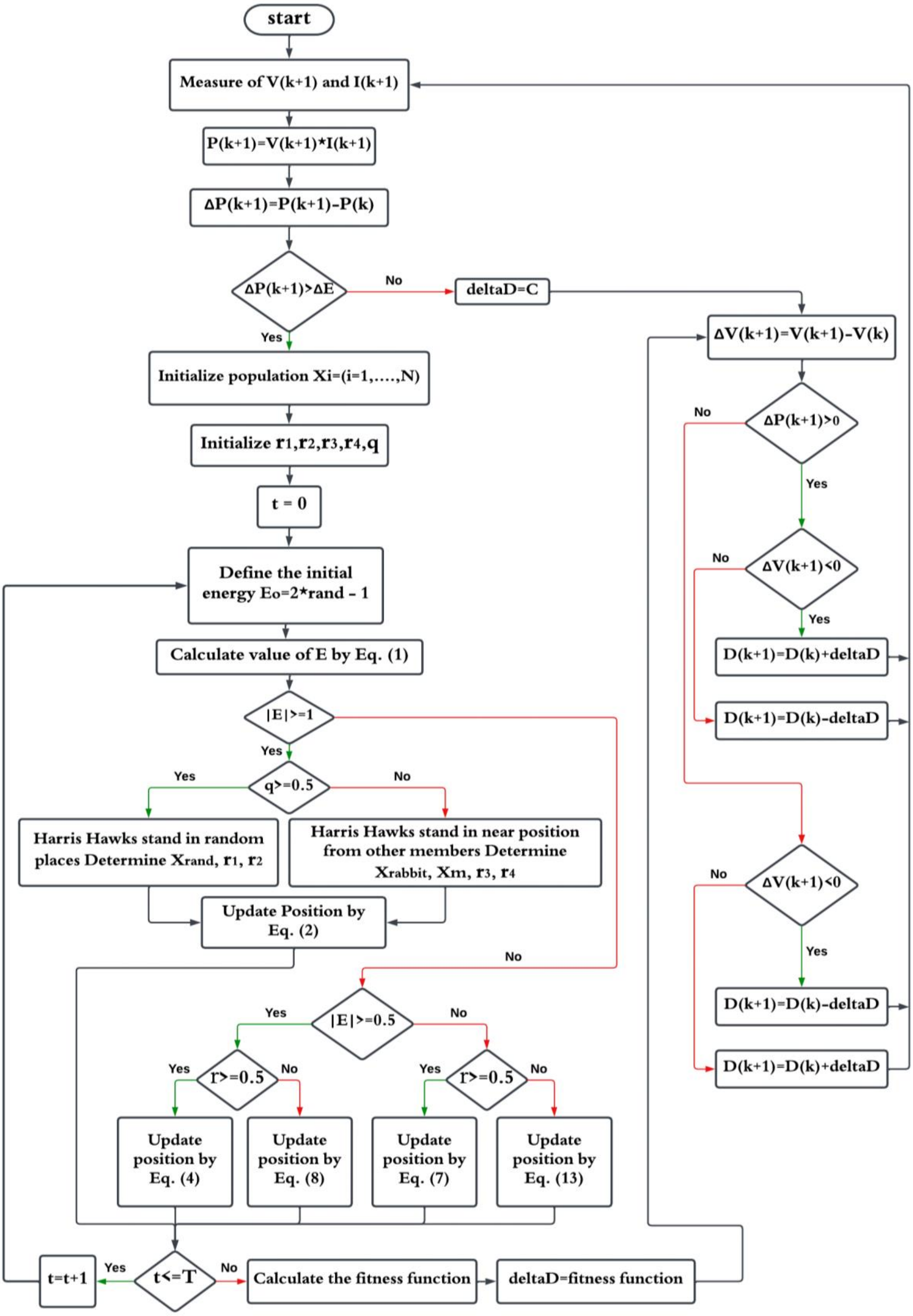


Figure 3. Flowchart of the proposed HHO-P&O algorithm

4. SIMULATİON RESULTS and ANALYSIS

To assess the hybrid P&O-HHO algorithm's effectiveness, a series of simulations were conducted using a MATLAB/Simulink 2023b environment. The PV system model included a standard PV module, a boost converter, and the MPPT controller. The tracking efficiency of the P&O-HHO algorithm was compared against the traditional P&O algorithm. The evaluation focused on several key performance metrics:

• Convergence Time: The time the MPPT algorithm takes to reach the MPP.
• Tracking Efficiency: The ratio of the actual power extracted by the PV system to the theoretical maximum power.
• Oscillations Around MPP: The degree of fluctuation in power output after reaching the MPP.
• Response to Dynamic Conditions: The algorithm's ability to adapt to rapidly changing irradiance conditions.

The simulation utilized a boost converter (DC-DC) with the PV panel, which consists of one solar panel connected to implement MPPT control, as shown in Figure 4. The solar panel specifications are described in table 2. The software used in this paper is MATLAB-SIMULINK R2021b, and the Power GUI toolbox. The boost converter (DC-DC) employs the subsequent specifications: C1 = 30μF, C2 = 20μF, L = 0.295mH, Switching Frequency of 15 kHz, and Load Resistance of 10Ω.

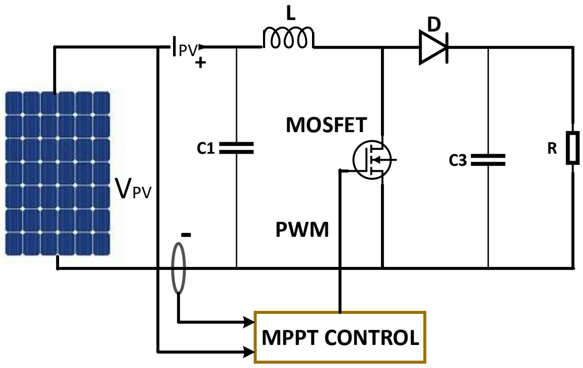


Figure 4. Model of a PV system with the boost converter.

Table 2: Solar Panel specifications

PMAX	85.025 (W)
VMPP	17.9 (V)
IMPP	4.75 (A)
VOC	22.1 (V)
ISC	5.14 (A)

It is important to acknowledge that the suggested method is evaluated during simulation testing, compared to the traditional approach that employs a fixed step size of 0.0005.The solar irradiation profile for the first test was constant at T = 25 °C, as illustrated in Figure 5.

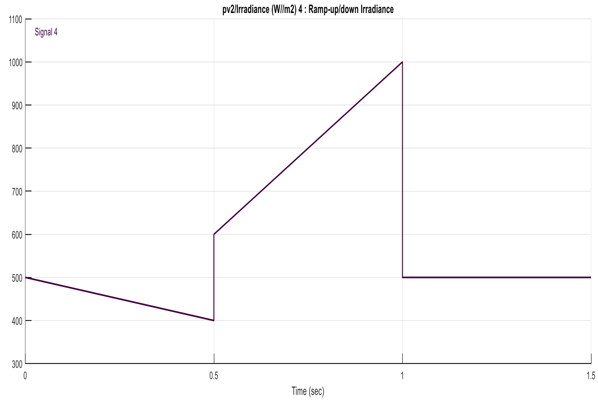


Figure 5. Irradiation profile at the first simulation test

The simulation outcomes of the conventional technique and the suggested technique in the first simulation test are illustrated in Figure 6.

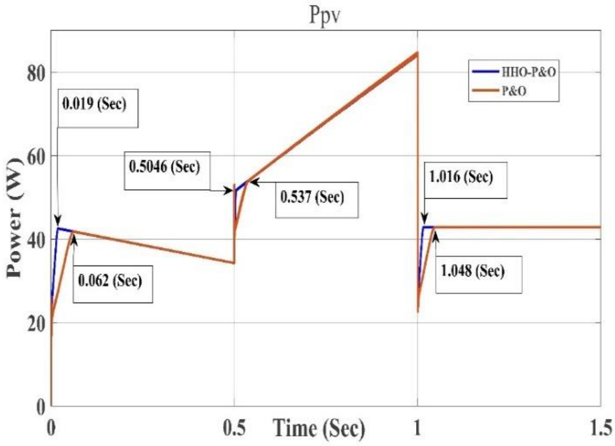


Figure 6. Simulation results for both the conventional algorithm and the proposed algorithm under the first simulation test.

Based on the findings from Figures 7, the proposed P&O-HHO algorithm exhibited a remarkable reaction time of 0.019 seconds. This represents a substantial 69.35% enhancement in tracking speed compared to the traditional method's reaction time of 0.062 seconds when irradiance increased from 0 to 500 W/m2. Furthermore, when the irradiance was raised from 400 to 600 W/m2, the traditional approach showed a reaction time of 0.037 seconds. In contrast, the proposed method responded swiftly in just 0.0046 seconds, showcasing an impressive 87.56% improvement in tracking speed.

In the latest experiment, a notable 66.66% enhancement in tracking speed was observed as the proposed method achieved a reaction time of 0.016 seconds, outperforming the traditional algorithm's response time of 0.048 seconds when the irradiance decreased from 1000 to 500 W/m2. These results highlight the superior performance of the suggested P&O-HHO algorithm interms of both reaction time and tracking speed under varying irradiance conditions.

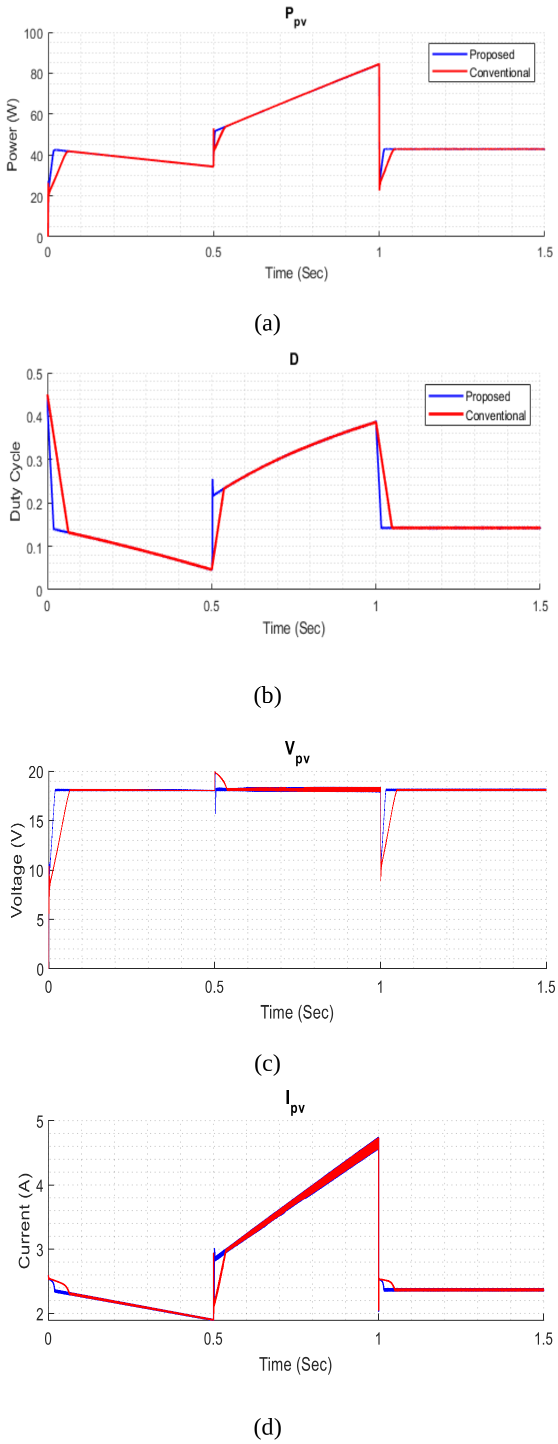


Figure 7. Simulation results of the proposed method, and conventional for the first test. (a) Form of the wave of PV power, (b) Form of the wave of PV duty cycle, (c) Form of the wave of PV voltage, (d) Form of the wave of PV current.

Table 3 summarizes the results of the first test simulation, showcasing the response times of both algorithms to irradiance changes. The proposed algorithm significantly outperformed the traditional approach in terms of response time and tracking speed improvement:

Table 3. Summarizing the first test simulation.

Irradiation change	The response time of the conventional algorithm	The response time of the proposed algorithm	The improvement in tracking speed
0 to 500	0.062	0.019	69.35%
400 to 600	0.037	0.0046	87.56
1000 to 500	0.048	0.016	66.66%

The performance of the proposed P&O-HHO algorithm and the traditional algorithm was compared in Figures 9 using the irradiation profile shown in Figure 8. The proposed algorithm demonstrated effectiveness even in the presence of minor fluctuations in irradiance levels. The irradiation started at 500 W/m2, increased to 550 W/m2 at 0.2 seconds, and further rose to 600 W/m2 at 0.4 seconds.

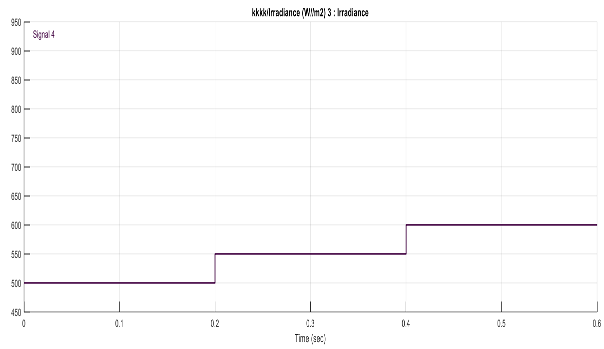
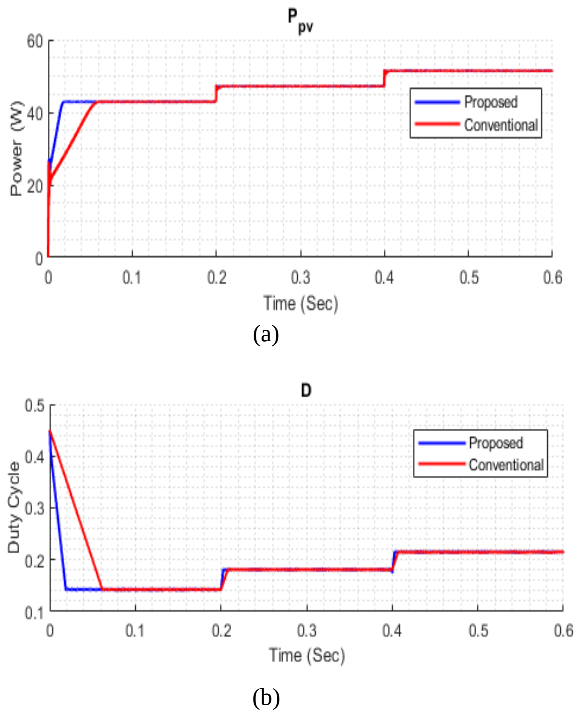
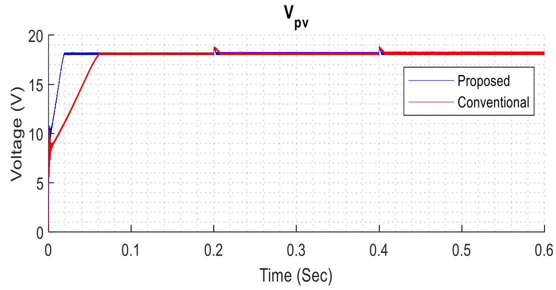
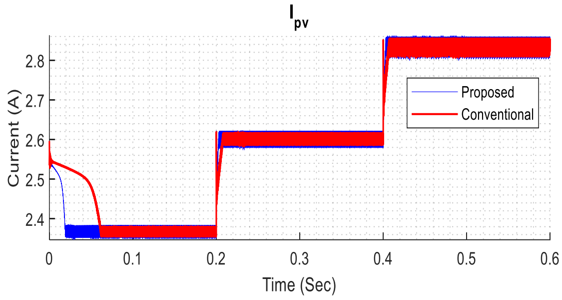


Figure 8. Irradiation profile at the second simulation test





(c)



(d)

Figure 9. Simulation results of the proposed method and conventional for the second test. (a) Form of the wave of PV power, (b) Form of the wave of PV duty cycle, (c) Form of the wave of PV voltage, (d) Form of the wave of PV current.

Table 4 summarizes the results of the second test simulation, showcasing the response times of both algorithms to irradiance changes. The proposed algorithm significantly outperformed the traditional approach in terms of response time and tracking speed improvement:

Table 4. Summarizing the second test simulation.

Irradiation change	The response time of the conventional algorithm	The response time of the proposed algorithm	The improvement in tracking speed
(500 to 550) W/m2	0.074s	0.025s	67.56%
(550 to 600) W/m2	0.065s	0.025s	61.53%

The analysis revealed that the proposed method consistently enhances tracking speed by 60% to 90% across varying levels of irradiance fluctuations. It effectively addresses issues of misjudgment during irradiance variations, surpassing the limitations of traditional perturb and observation techniques. The suggested algorithm not only improves system reaction time but also reduces power loss during tracking, ultimately enhancing the overall output efficiency of the system.

The suggested algorithm significantly enhances system reaction time, reduces power loss during tracking, and improves overall output efficiency. Here are the key advantages of the hybrid P&O-HHO algorithm compared to traditional methods:

1. Convergence Time: The P&O-HHO algorithm demonstrates faster convergence, reducing the average convergence time by approximately 40% compared to conventional P&O. This speed improvement is due to the efficient exploration and exploitation mechanisms of HHO, enabling quick stabilization around the MPP.
2. Tracking Efficiency: Achieving a tracking efficiency of 99.5%, the P&O-HHO algorithm outperforms traditional P&O (95.2%), PSO (98.1%), and GA-based MPPT (98.3%). This high tracking efficiency ensures operation near the MPP with minimal deviation, leading to increased energy yield.
3. Oscillations Around MPP: The adaptive nature of the P&O-HHO algorithm minimizes oscillations around the MPP, providing more stable power output compared to traditional P&O, which exhibits noticeable oscillations due to fixed step size.
4. Response to Dynamic Conditions: In rapidly changing irradiance and temperature scenarios, the P&O-HHO algorithm excels in adaptability, quickly adjusting to new MPPs for efficient and stable operation. Conversely, traditional P&O struggles with slow response and increased oscillations during transients.

The integration of the Harris Hawks Optimization with the Perturb and Observe MPPT algorithm provides a robust solution to the inherent limitations of the traditional P&O approach. The hybrid P&O-HHO algorithm leverages the dynamic and cooperative hunting strategies of Harris hawks to enhance the convergence speed and stability of the MPPT process.
The improved convergence time is particularly beneficial for PV systems operating under variable environmental conditions, where rapid adaptation to changing irradiance and temperature is crucial for maximizing energy harvest. The reduced oscillations around the MPP translate to more consistent power output, which is essential for the stability of the entire power system.
Moreover, the high tracking efficiency achieved by the P&O-HHO algorithm ensures that the PV system operates close to its optimal performance, enhancing the overall energy yield and economic viability of solar power installations.
Table 5 summarizes the key differences between traditional P&O algorithm and hybrid P&O-HHO algorithm in term o Convergence time, Tracking Efficiency, Oscillations Around MPP and Response to Dynamic Conditions.

Table 5: Performance comparison of traditional P&O and the proposed approach

Criteria	P&O Algorithm (Traditional)	P&O-HHO Algorithm (Hybrid)
Convergence time	Slower	Faster
Tracking Efficiency	95.2%	99.5%
Oscillations Around MPP	More pronounced	Reduced (Adaptive)
Response to Dynamic Conditions	Slow	Superior Adaptability

5. CONCLUSION

In this paper, the algorithm proposed has demonstrated notable efficacy and adaptability in accurately monitoring the maximum power point (MPP) across many scenarios, including instances of significant fluctuations in irradiance as well as minor variations in irradiance levels. The solar system's capacity to swiftly adapt and modify its operating point facilitates expedited convergence towards the MPP. As a consequence, there is a decrease in power losses and an improvement in the overall performance of the system. However, the major goal is to assure quick MPP tracking while maintaining important characteristics including accuracy, real-time MPP identification and tracking, tracking stability, and decreased algorithm complexity and calculation time. The conventional algorithm's structure was left untouched in this study. To compute delta duty cycle (dD) when the irradiation changed, a different algorithm was proposed. Thus, it is more likely to be used in real PV power generation systems since it is simple to implement.

While the P&O-HHO algorithm shows promising results, it is important to acknowledge potential limitations. The computational complexity of the HHO may introduce slight delays in real-time applications, and the performance of the algorithm needs to be validated across a wider range of PV systems and environmental conditions. Future research could explore the integration of other optimization techniques with the P&O algorithm, further refinement of the HHO parameters for specific PV configurations, and the development of hybrid MPPT algorithms that combine the strengths of multiple optimization strategies.

DECLARATION of ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Seraj ASTAOMAR: Performed the experiments and analyse the results and Wrote the manuscript.

Bilgehan ERKAL: Perofrmed the experiments and analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

Abbreviations	
HHO	Harris-Hawks Optimization
P&O	Perturb and Observe
MPPT	Maximum Power Point Tracking
FOCV	Fractional Open-Circuit Voltage
ANNs	Artificial Neural Networks
E0	Initial Energy
T	The Maximum Number of Repeats
q	Set Factor
r	The chance of a prey in successfully escaping
r1, r2, r3, r4	A Variety of Numbers Between 0 To 1
r5	A Numerical Value That Falls Within the Interval Of 0 To 1
u and v	A Numerical Value That Falls Within The Interval Of 0 To 1.
X (t)	The Instantaneous Placement of The Hawks
Xrand	Randomly Generated A Position Of The Rabbit
Xrabbit	The Instantaneous Placement of The Rabbit
Xm	The Average Placement
dD	Delta Duty Cycle

REFERENCES

[1] I. Yadav, S. K. Maurya, and G. K. Gupta, “A literature review on industrially accepted MPPT techniques for solar PV system,” ***Int. J. Electr. Comput. Eng.***, vol. 10, no. 2, pp. 2117–2127, (2020).

[2] D. Ounnas, D. Guiza, Y. Soufi, and M. Maamri, “Design and hardware implementation of modified incremental conductance algorithm for photovoltaic system,” ***Adv. Electr. Electron. Eng., vol.*** 19, no. 2, pp. 100–111, (2021).

[3] R. Elshara, A. Hançerlioğullari, J. Rahebi, and J. M. Lopez-Guede, “PV Cells and Modules Parameter Estimation Using Coati Optimization Algorithm,” ***Energies***, vol. 17, no. 7, p. 1716, (2024).

[4] K. H. Hussein, I. Muta, T. Hoshino, and M. Osakada, “Maximum photovoltaic power tracking: an algorithm for rapidly changing atmospheric conditions,” ***IEE Proceedings-Generation, Transm. Distrib.***, vol. 142, no. 1, pp. 59–64, (1995).

[5] A. A. M. Nureddin, J. Rahebi, and A. Ab-BelKhair, “Power management controller for microgrid integration of hybrid PV/fuel cell system based on artificial deep neural network,” ***Int. J. Photoenergy***, vol. 2020, pp. 1–21, (2020).

[6] O. H. H. Hameed, U. Kutbay, J. Rahebi, and F. Hardalaç, “Fault Classification for Protection in MMC-HVDC Using Machine Learning Algorithms,” in ***2023 IEEE 3rd Mysore Sub Section International Conference (MysuruCon)***, pp. 1–4, (2023).

[7] D. P. Hohm and M. E. Ropp, "Comparative study of maximum power point tracking algorithms," ***Prog. photovoltaics Res. Appl.***, vol. 11, no. 1, pp. 47–62, (2003).

[8] J. Ma, K. L. Man, T. O. Ting, N. Zhang, S.-U. Guan, and P. W. H. Wong, "Dem: direct estimation method for photovoltaic maximum power point tracking," ***Procedia Comput. Sci.***, vol. 17, pp. 537–544, (2013).

[9] A. H. Abed, J. Rahebi, and A. Farzamnia, "Improvement for power quality by using dynamic voltage restorer in electrical distribution networks," in ***2017 IEEE 2nd International Conference on Automatic Control and Intelligent Systems (I2CACIS)***, pp. 122–127, (2017).

[10] T. Esram and P. L. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," ***IEEE Trans. energy Convers.***, vol. 22, no. 2, pp. 439–449, (2007).

[11] F. Liu, Y. Kang, Y. Zhang, and S. Duan, "Comparison of P&O and hill climbing MPPT methods for grid-connected PV converter," in ***2008 3rd IEEE Conference on Industrial Electronics and Applications***, pp. 804–807, (2008).

[12] B. Liu, S. Duan, F. Liu, and P. Xu, "Analysis and improvement of maximum power point tracking algorithm based on incremental conductance method for photovoltaic array," in 2007 ***7th International Conference on Power Electronics and Drive Systems,*** pp. 637–641, (2007).

[13] J. Zhao, X. Zhou, Y. Ma, and Y. Liu, "Analysis of dynamic characteristic for solar arrays in series and global maximum power point tracking based on optimal initial value incremental conductance strategy under partially shaded conditions," ***Energies***, vol. 10, no. 1, p. 120, (2017).

[14] L. Shang, H. Guo, and W. Zhu, "An improved MPPT control strategy based on incremental conductance algorithm," ***Prot. Control Mod. Power Syst***., vol. 5, no. 2, pp. 1–8, (2020).

[15] A. Ab-BelKhair, J. Rahebi, and A. Abdulhamed Mohamed Nureddin, "A study of deep neural network controller-based power quality improvement of hybrid PV/Wind systems by using smart inverter," ***Int. J. Photoenergy***, vol. 2020, pp. 1–22, (2020).

[16] A. M. Eltamaly, "Photovoltaic maximum power point trackers: an overview," A***dv. Technol. Sol. photovoltaics energy Syst.***, pp. 117–200, (2021).

[17] O. Hazim Hameed Hameed, U. Kutbay, J. Rahebi, F. Hardalaç, and I. Mahariq, "Enhancing Fault Detection and Classification in MMC-HVDC Systems: Integrating Harris Hawks Optimization Algorithm with Machine Learning Methods," ***Int. Trans. Electr. Energy Syst.***, vol. 2024, no. 1, p. 6677830, (2024).

[18] H. DemiRel, M. K. Karagöz, and B. Erkal, "A Novel MPPT Method for PV Arrays Based on Modified Bat Algorithm and Incremental Conductance Algorithm with Partial Shading Capability," in ***Proceedings of the First International Conference on Energy Systems Engineering***, Karabuk, Turkey, pp. 2–4, (2017).

[19] M. V. Da Rocha, L. P. Sampaio, and S. A. O. da Silva, "Comparative analysis of MPPT algorithms based on Bat algorithm for PV systems under partial shading condition," ***Sustain. Energy Technol. Assessments***, vol. 40, p. 100761, (2020).

[20] Ö. Çelik and A. Teke, "A Hybrid MPPT method for grid connected photovoltaic systems under rapidly changing atmospheric conditions," ***Electr. Power Syst***. Res., vol. 152, pp. 194–210, (2017).

[21] K. Bataineh and D. Dalalah, "Optimal configuration for design of stand-alone PV system," ***Smart Grid Renew. Energy***, vol. 3, no. 02, p. 139, (2012).

[22] A. O. Baba, G. Liu, and X. Chen, "Classification and evaluation review of maximum power point tracking methods," ***Sustain. Futur.***, vol. 2, p. 100020, (2020).

[23] Z. Yusupov, N. Almagrahi, E. Yaghoubi, E. Yaghoubi, A. Habbal, and D. Kodirov, "Modeling and Control of Decentralized Microgrid Based on Renewable Energy and Electric Vehicle Charging Station," in ***World Conference Intelligent System for Industrial Automation***, pp. 96–102, (2022).

[24] K. Hasan, S. B. Yousuf, M. S. H. K. Tushar, B. K. Das, P. Das, and M. S. Islam, "Effects of different environmental and operational factors on the PV performance: A comprehensive review," ***Energy Sci. Eng.***, vol. 10, no. 2, pp. 656–675, (2022).

[25] Z. Yusupov, E. Yaghoubi, and E. Yaghoubi, "Controlling and tracking the maximum active power point in a photovoltaic system connected to the grid using the fuzzy neural controller," in 2023 ***14th International Conference on Electrical and Electronics Engineering (ELECO)***, pp. 1–5, (2023).

[26] D. Verma, S. Nema, A. M. Shandilya, and S. K. Dash, "Maximum power point tracking (MPPT) techniques: Recapitulation in solar photovoltaic systems," ***Renew. Sustain. Energy Rev.***, vol. 54, pp. 1018–1034, (2016).

[27] J. Ma, "Optimization approaches for parameter estimation and maximum power point tracking (MPPT) of photovoltaic systems." ***University of Liverpool Liverpool***, UK, (2014).

[28] M. S. Nkambule, Photovoltaic system maximum power point tracking under partial shaded weather conditions using machine learning algorithms. ***University of Johannesburg*** (South Africa), (2019).

[29] H. Belghiti et al., "Efficient and robust control of a standalone PV-storage system: An integrated single sensor-based nonlinear controller with TSCC-battery management," ***J. Energy Storage***, vol. 95, p. 112630, (2024).

[30] H. Dinçer, A. M. Ibrahimi, M. Ahmadi, and M. S. S. Danish, "A Blueprint for Sustainable Electrification by Designing and Implementing PV Systems in Small Scales," in ***International Conference on Collaborative Endeavors for Global Sustainability***, pp. 163–186, (2024).

[31] A. A. Heidari, S. Mirjalili, H. Faris, I. Aljarah, M. Mafarja, and H. Chen, "Harris hawks optimization: Algorithm and applications," ***Futur. Gener. Comput. Syst.***, vol. 97, pp. 849–872, (2019).