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Performance comparison of hybrid MPPT methods in MATLAB/Simulink environment: An approach for partial shading situation

MATLAB/Simulink ortamında hibrit MPPT yöntemlerinin performans karşılaştırması: kısmi gölgeleme durumları için bir yaklaşım

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Abstract

This paper proposes a novel hybrid maximum power point tracking (MPPT) technique for photovoltaic (PV) systems under partial shading situations. The proposed method is based on Incremental Conductance and Particle Swarm Optimization MPPT techniques. Different irradiance levels have been used to evaluate the presented hybrid approach in MATLAB/Simulink. Both the Constant Voltage-Particle Swarm Optimization hybrid MPPT and the Hill Climbing-Particle Swarm Optimization hybrid MPPT techniques have been used for comparison with the proposed approach. Hybrid methods that combine traditional algorithms with the nature-inspired PSO algorithm have been developed to utilize the advantages of the algorithms. Simulation results show that the presented MPPT technique has high tracking accuracy, 98.60% efficiency, average output power of 23.063 kW, time to reach the maximum power point of 0.001 seconds, and power ripple of 0.3 kW under partial shading conditions. As a result, the proposed method gives the best results compared to other hybrid algorithms and outperforms other hybrid algorithms.

Keywords: Maximum power point, Maximum power point tracking, MPPT methods, Partial shading conditions, Photovoltaic system

Öz

Bu makale, kısmi gölgeleme koşullarında fotovoltaik (FV) sistemler için yeni bir hibrit maksimum güç noktası izleyicisi (MGNİ) tekniği önermektedir. Önerilen yöntem, Artımlı İletkenlik ve Parçacık Sürüsü Optimizasyonu MGNİ tekniklerine dayanmaktadır. Sunulan hibrit yaklaşımın MATLAB/Simulink'te değerlendirilmesinde farklı ışınım seviyeleri kullanılmıştır. Önerilen yaklaşımla karşılaştırmak için hem Sabit Voltaj-Parçacık Sürüsü Optimizasyonu hibrit MPPT hem de Tepe Tırmanış-Parçacık Sürüsü Optimizasyonu hibrit MPPT teknikleri kullanılmıştır. Geleneksel algoritmalar ile doğa esinli algoritma olan PSO algoritmasını birleştiren hibrit yöntemler geliştirilerek algoritmaların avantajlarından faydalanılmıştır. Simülasyon sonuçlarında, kısmi gölgeleme durumlarında sunulan MPPT tekniğinin, izleme doğruluğunun yüksek, verimliliğinin %98.60, ortalama çıkış gücünün 23.063 kW, maksimum güç noktasına ulaşma süresinin 0.001 saniye ve güç dalgalanmasının 0.3 kW olduğu görülmüştür. Sonuç olarak, önerilen yöntem diğer hibrit algoritmalara göre en iyi sonuçları vermiş olup, diğer hibrit algoritmalardan daha iyi performans göstermektedir.

Anahtar kelimeler: Maksimum güç noktası, Maksimum güç noktası izleyicisi, MPPT metotları, Kısmi gölgelenme durumları, Fotovoltaik sistem

1 Introduction

Energy is essential to contemporary civilization. Consequently, energy has come to be associated with societal growth and progress [1]. Energy has a crucial role in maintaining a country's growth [2]. The utilization of several traditional energy sources is a result of the growing need for energy in advancing society [3]. Non-renewable energy sources are widely used in energy production, which is the primary cause for worry [4]. There is an urgent need for research on environmentally friendly and renewable energy alternatives due to the fast depletion of fossil fuels, which provide about 80% of the world's energy [5]. The long-term usage of these fuels has resulted in several environmental risks, including air and water pollution and dangers to different kinds of animals. Using these traditional energy sources for so long has led to negative repercussions such as acid rain, soil erosion, and climate change [6]. One of the main causes of modern climate change is the increased atmospheric concentration of carbon dioxide brought on by burning fossil fuels [4]. Using clean and affordable renewable energy sources that are appropriately managed and utilized is the world's problem in the fight against global warming and climate change [2]. An alternate method of producing energy to lower greenhouse gas releases is the utilization of green forms of energy [7]. Three of the seventeen United Nations 2030 objectives include reference to renewable energy, of which solar energy is a key component [8]. Around the world, there is a lot of interest in using renewable energy as the next source of energy.

One abundant, renewable, and sustainable energy source is solar energy [5]. Large, plentiful, free, and

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environmentally friendly, solar energy is a clean power source [3]. Solar energy appears to be a strong substitute for fossil fuels. Solar PV cell technology has become increasingly popular as a sustainable energy source as concerns about how traditional energy sources contribute to climate change and global warming have grown [4]. In our world that is power-thirsty, there has been a growing need for solar energy [1]. With the rise in global electricity consumption, photovoltaic systems are becoming increasingly well-known [2]. But in the past several years, solar energy production has emerged as one of the most well-known renewable technologies due to its simplicity of installation, cheap running costs, and advanced technology [7]. As technology advances at a quick pace, PV modules are becoming more efficient and PV module prices are decreasing [9]. In order to combat climate change, lower energy costs, increase power supply stability, and provide access to power, solar photovoltaics are significant contributors to renewable energy sources [10]. Photovoltaic panels now account for a significant portion of all power generating [11].

With solar PV systems, power can be generated from the sun [2]. The transformation of incoming solar irradiation to electrical energy is the focus of solar PV technology [6]. In 1839, physicist Becquerel made the first observation of this phenomenon, which is known as the photovoltaic effect. Due to its green nature and lack of pollution, solar energy has made it possible to offset the use of fossil fuels by developing PV cells [12].

A PN junction, which operates on the photovoltaic effect principle, is a more traditional type of solar cell [6]. Electrons move in a single direction and holes flow in the other way in a solar cell, causing current to flow in the hole direction. The overall current is directly affected by the electrons that are captured. Consequently, it may be said that the current produced by solar cells varies according to the light's intensity [12]. A photovoltaic cell generates direct current (DC) electricity as sunlight strikes it [6]. Although the possibility of solar energy has been known for thousands of years, it took hundreds of years to develop systems for collecting energy that could capture the sun's light and transform it into electrical power [4].

At different irradiation intensities and PV cell temperatures, the efficiency of PV modules is assessed using their current-voltage (I-V) characteristic [11]. A single moment during operation, known as the maximum power point (MPP), is where the PV module's nonlinear function produces its greatest power. Consequently, it is necessary to optimize the energy delivered from the PV module to the load. This can be accomplished by employing an MPPT monitor to operate the PV system in MPPT mode. The most widely used methods ever developed to improve PV system performance and maximize the amount of solar energy that may be used are MPPT controllers. These systems' main advantages are their environmental friendliness, ease of implementation, and unconditional energy reliability [2].

Solar photovoltaics have long been associated with high prices and advanced technology. This problem has prompted experts to come up with creative alternatives and put the current solar power technology to the test [1]. In summary, our ever-increasing energy needs might be met by sunlight that reaches the Earth's surface [6].

Previous studies have proposed different MPPT methods to address partial shading issues. With the increasing energy demand and advancements in PV technology, different MPPT methods continue to be investigated. Because many factors influence the MPP point, MPPT methods differ from each other in terms of their characteristics.

Koshkarbay et al. [13] introduced a Social Spider Optimization (SSO) method for changing loads and partial shading conditions in PV systems. The proposed approach has fast MPP tracking, good algorithm accuracy, better efficiency and better performance than other metaheuristic algorithms compared in the work. Sridhar and Kumar [14] presented a Crayfish-Optimized Neuro-Fuzzy Inference (CO-RNFIS) MPPT technique for PV-wind systems. The results indicated better results in efficiency, MPP tracking, and reducing harmonics. Krishnaram et al. [15] developed a novel Water Cycle Optimization (WCO) and Incremental Conductance (InC)-based MPPT method with experimental PV data. The method used was compared with Perturb and Observe (P&O), InC, Water Cycle Algorithm (WCA), and WCO-P&O hybrid MPPT methods. Validation tests confirmed its ability to show low oscillation amount, fast MPP convergence time and better MPP tracking performance. Ram et al. [16] proposed a P&O-assisted Flower Pollination Algorithm (FPA) MPPT algorithm to enhance photovoltaic system performance. Simulation results showed improved fast MPP convergence, good power efficiency, and low switching stress, compared to other comparative methods. Aguila-Leon et al. [17] investigated a Grey Wolf Optimization (GWO)-based MPPT strategy. In the study, four different metaheuristic algorithms were compared: Particle Swarm Optimization (PSO), Wolf Optimizer Algorithm (WOA), GWO, and Simulated Annealing (SA). Simulations revealed higher output power, faster MPP tracking, and better performance compared to other metaheuristic and traditional MPPT algorithms. Moustaine et al. [18] introduced the Dichotomous Search-based MPPT algorithm. The proposed algorithm, which consists of two stages including Open Circuit Voltage (V_{OC}) and Sliding Mode Controller (SMC), is compared with Fuzzy Logic Controller (FLC), VS-Backstepping and Inc-Proportional-Integral (PI) MPPT methods. The proposed approach has good efficiency, fast MPPT response, good MPPT accuracy, and lower oscillation than other algorithms in the work. Yaghoubi et al. [19] presented a modified Salp Swarm Optimization (SSO) method for PV model parameter extraction. The proposed metaheuristic method has been tested using various test functions. The approach achieved higher performance, safer and more accurate MPP tracking in varying weather conditions. Long et al. [20] developed a new GWO and Cuckoo Search Algorithm (CSA) based hybrid algorithm for parameter extraction of PV modules. Experimental analysis confirmed better or similar result accuracy, better solution precision, and better MPP convergence speed than other algorithms compared in the study. Aboutorabi and Sarvi [21] proposed a new hybrid

Combined PSO-Biogeography-based Optimization algorithm. This method, which was created by hybridizing the Modified Biogeography-based Optimization (MBBO) and Modified Particle Swarm Optimization (MPSO) algorithms, was compared with the GA, P&O, MPSO and MBBO algorithms. Simulations and experimental results showed that it has better MPPT accuracy and faster MPPT response time. Mai et al. [22] applied a novel MPPT based on the Dung Beetle Optimization (DBO) algorithm for partial shading circumstances in PV systems. This algorithm is inspired by the way dung beetles use environmental information to search for and hide prey in nature. In the study, it was concluded that the proposed method has a better MPP convergence rate, better maximum output power, and better MPP efficiency compared with many advanced algorithms. Rocha et al. [23] implemented Bat Algorithm-based MPPT algorithms for PV systems. These algorithms were created by hybridizing the InC, P&O and Beta (β) algorithms with the Bat algorithm. These algorithms were compared by setting up test scenarios. The findings demonstrated that the Bat-Beta hybrid MPPT algorithm showed the best overall performance with respect to other hybrid algorithms. Reddy et al. [24] proposed a Solar Charge Controller with Hill Climbing (HC) MPPT method. According to simulation and experimental results, the proposed system has an efficient battery charging feature, higher efficiency, and accurate MPP tracking. Duman et al. [25] presented a new Teaching-learning-based Artificial Bee Colony (TLABC) MPPT technique combining Teaching-learning (TL) and Artificial Bee Colony (ABC) for PV systems. The results indicated better accuracy, stable structure, and better overall performance. Manna et al. [26] proposed a new adaptive Model Reference Adaptive Control (MRAC) MPPT method. The applied method was compared with the P&O and InC methods, and lower voltage and current swing, better efficiency, and better MPP convergence speed were observed. Yuwanda et al. [27] presented a modified P&O MPPT method that includes Constant Power Generation (CPG) and MPPT operating modes. The proposed system in the study was tested in a simulation environment and it was observed that it prevented overvoltage in the PV system and provided constant voltage to the system. Dinesh and Eti [28] applied an Optimized InC approach for the battery-PV system. In the system containing the battery and supercapacitor, the proposed method has been shown to have better efficiency, low oscillation, reliability and fast convergence compared to traditional algorithms. Manoharan et al. [29] developed an improved P&O algorithm for PV systems. In addition to the classic P&O parameters, changes in the current are taken into account. Modified Perturb and Observe (MP&O) and Adaptive Modified Perturb and Observe (AMPO) are the two methods proposed in this study. Results analysis confirmed faster MPPT response, faster MPP tracking time and higher efficiency than other compared methods.

In this study, a hybrid MPPT technique based on the Incremental Conductance and Particle Swarm Optimization MPPT method is presented. The presented method has been tested in the MATLAB/Simulink R2016b program with varying irradiance conditions. The Constant Voltage-Particle Swarm Optimization MPPT and the Hill Climbing-Particle Swarm Optimization MPPTs have also been tested in the test scenarios. The test results indicate that the presented approach provides better results in terms of MPP tracking, speed, accuracy, and performance.

This study's primary contributions are as follows: The proposed method increases the output power of the boost converter and PV system. The recommended approach reduces steady-state oscillations in partial shading. The proposed method improves MPP convergence speed and converter output efficiency. The results of hybridizing classical algorithms with nature-based algorithms have been investigated.

The remainder of the document is structured as follows. In Section 2, the study's goal, methodology, and PV system features are covered. Section 3 discusses the characteristics of the simulated situations. Lastly, the study's findings and interpretations are provided in Section 4.

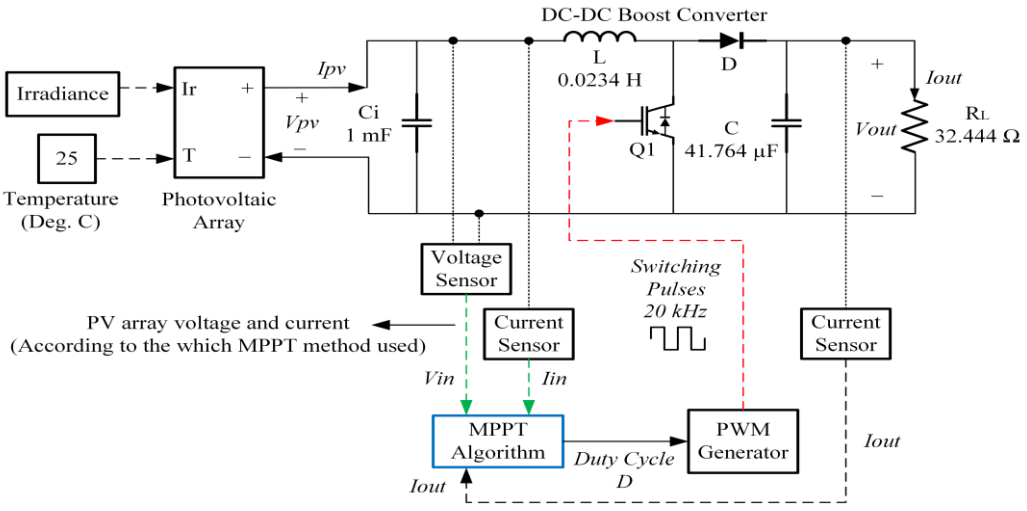


Figure 1. Block schematic of the PV system

2 Design of the PV system

In this study, PV system simulations involving the presented hybrid approach and different hybrid methods have been prepared in the simulation environment. The system, which consists of the PV array, DC-DC boost converter, and converter control circuit, is set up separately for each simulation. PV array voltage, PV array current, and converter output current values are measured according to the requirements of the MPPT algorithm used in the system. These values are sent into the generated MPPT algorithms, and the algorithms are run. The algorithms are executed within a MATLAB function block. Each algorithm generates the appropriate duty cycle value as output. This generated duty cycle is then transmitted to the Pulse Width Modulation (PWM) generator. Then, it generates a PWM signal, activating the DC-DC boost converter. Finally, the DC-DC converter increases the voltage produced by the PV array, and the MPPT operation is performed. The block schematic of the PV system is shown in Figure 1.

2.1 PV system

In this work, SunPower SPR-440NE-WHT-D model PV modules have been utilized in the designed PV system. The I-V graphs of the PV module used are shown in Figure 2.

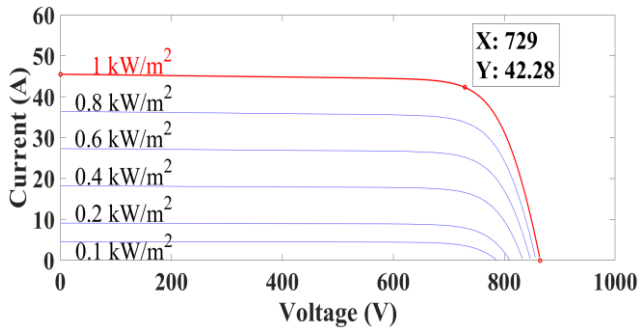


Figure 2. I-V characteristics of the PV module used in the system

The P-V graphs of the PV module used are shown in Figure 3.

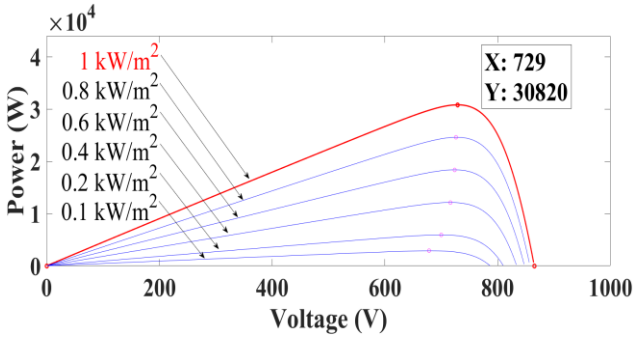


Figure 3. P-V properties of the PV module that is utilized in the system

Table 1 shows the characteristics of the PV module used in the system. The desired power level has been achieved by creating series and parallel-connected modules in the PV system. The parameters of the designed PV system are given in Table 2.

Table 1. Label parameters of the PV module

Features	Values	Units
Maximum Output Power (P_{max})	440.316	W
Power at STC	440	W
Power at PTC	404.9	W
Open Circuit Voltage (V_{oc})	86.5	V
Voltage at MPP (V_{mpp})	72.9	V
Short Circuit Current (I_{sc})	6.5	A
Current at MPP (I_{mpp})	6.04	A
Cells per Module (N_{cell})	128	Pcs.
Temperature Coefficient of V_{oc}	−0.326	%/°C
Temperature Coefficient of I_{sc}	0.019308	%/°C
Max Power Temperature Coefficient	−0.424	%/°C
Power Density at STC	203.704	W/m^2
Power Density at PTC	187.454	W/m^2
Nominal Operating Cell Temperature	44.6	°C

Table 2. Parameters of the PV system

Features	Values	Units
Maximum Output Power (P_{max})	30 822.12	W
Number of Strings	7	Pcs.
Number of Modules in a String	10	Pcs.
Number of Total PV Modules	70	Pcs.
Total Output Voltage (V_{pv})	729	V
Total Output Current (I_{pv})	42.28	A

Equation 1 depicts the PV array's output voltage.

$$V_{pv} = N_{series} \times V_{mpp} = 10 \times 72.9\ \text{V} = 729\ \text{V} \quad (1)$$

Equation 2 represents the PV array's output current.

$$I_{pv} = N_{parallel} \times I_{mpp} = 7 \times 6.04\ \text{A} = 42.28\ \text{A} \quad (2)$$

The PV array's output power is determined with Equation 3.

$$P_{pv} = N_{total} \times P_{max} = 70 \times 440.316\ \text{W} = 30.822\ \text{kW} \quad (3)$$

In the implemented system, a PV array block has been added for the PV module. A fixed temperature of 25 degrees Celsius has been selected as the temperature data, while irradiance data has been obtained from the signal builder block, which contains variable irradiance data.

2.2 DC-DC boost converter

Within the PV system, a DC-DC boost converter circuit has been added to the PV array output. The converter increases the PV array output voltage from 729 V to 1000 V. The DC-DC boost converter includes an IGBT/diode, an inductor, a resistor, capacitors, and a diode. The IGBT/diode in the converter is triggered at 20 kHz. The values of the boost converter circuit elements are calculated using the following equations [30-34].

The boost converter's duty cycle (D) is represented in Equation 4.

$$D = \left(1 - \frac{V_{in}}{V_{out}}\right) = 0.2710 = 27.10\%\text{V} \quad (4)$$

Equation 5 demonstrates the converter's output current.

$$I_{out} = \frac{P_{out}}{V_{out}} = 30.822\ \text{A} \quad (5)$$

Equation 6 illustrates the converter's current ripple.

$$\Delta I_{out} = 0.1 \times I_{out} = 3.0822\ \text{A} \quad (6)$$

The load resistance is calculated in Equation 7.

$$R_L = \frac{V_{out}}{I_{out}} = 32.444\ \Omega \quad (7)$$

Equation 8 shows the voltage ripple value of the boost converter.

$$\Delta V_{out} = 0.01 \times V_{out} = 10\ \text{V} \quad (8)$$

The boost converter's inductor current ripple is calculated in Equation 9.

$$\Delta I_L = 0.01 \times I_{out} \times \frac{V_{out}}{V_{in}} = 0.423\ \text{A} \quad (9)$$

Equation 10 gives the inductance value.

$$L = \frac{V_{in} \times (V_{out} - V_{in})}{f_{sw} \times \Delta I_L \times V_{out}} = 0.0234\ \text{H} \quad (10)$$

Here, Equation 11 shows the capacitor value.

$$C = \frac{I_{out} \times D}{f_{sw} \times \Delta V_{out}} = 41.764\ \mu\text{F} \quad (11)$$

Table 3 demonstrates all the determined DC-DC boost converter circuit elements' parameters.

Table 3. Calculated values of the boost converter

Features	Values	Units
Inductor (L)	0.0234	H
Load Resistor (R_L)	32.444	Ω
Capacitor (C)	41.764	µF
Current Ripple (ΔI_{out})	3.0822	A
Inductor Current Ripple (ΔI_L)	0.423	A
Voltage Ripple (ΔV_{out})	10	V
Switching Frequency (f_{sw})	20	kHz
Output Voltage (V_{out})	1000	V
Input Voltage (V_{in})	729	V
Output Current (I_{out})	30.822	A
Input Current (I_{in})	42.28	A
Duty Cycle (D)	27.10	%

2.3 Control strategy of the DC-DC boost converter

The IGBT/diode in the boost converter is switched using MPPT algorithms. The duty cycle information generated in the MATLAB function block is fed into the PWM generator. The appropriate PWM signal is produced with the duty cycle value. The generated PWM signal is fed into the converter's switching element, operating the converter at the appropriate values. Different MPPT algorithms produce different duty cycle values, permitting a variety of working circumstances for the converter.

2.3.1.1 Hybrid MPPT methods

Methods that combine multiple MPPT techniques are known as hybrid MPPT techniques. Hybrid algorithms combine the advantages of different MPPT methods to achieve efficient MPP tracking. Three distinct hybrid algorithms have been created and evaluated in this work using the MATLAB/Simulink environment. In this study, Constant Voltage-Particle Swarm Optimization, Hill Climbing-Particle Swarm Optimization, and Incremental Conductance-Particle Swarm Optimization hybrid algorithms have been selected for comparison and testing. These methods have been chosen due to their rapid convergence feature, simple algorithm creation, lack of additional sensor requirements, and hybridizability compatible with the PSO algorithm. The Constant Voltage method provides approximate MPP tracking, and the Hill Climbing method has steady state oscillation. The proposed method can provide more sensitive and accurate MPP tracking. It has been examined that fast dynamic response advantages of classical MPPT methods and the high MPP tracking accuracy advantages of metaheuristic methods.

2.3.1.2 Constant voltage and particle swarm optimization MPPT

An approximately constant value is obtained by dividing the open circuit voltage value of the PV array by the voltage value at the MPP. It is typically around 0.76 times of the PV module's open circuit voltage for any specific solar irradiation. The Constant Voltage (CV) algorithm is based on this. It is simple to build a CV control using analogue circuitry. Using the procedure shown below in Figure 4, the CV MPPT method may be put into practice [35].

The CV algorithm begins by setting the reference voltage. The voltage at the converter input is then measured. If the preset reference voltage is equal to the measured voltage at the converter input, MPP tracking is considered. If not, the input voltage is examined to determine whether it is greater than the reference voltage. If greater, a specific increase in the duty cycle value is applied. If less, a specific decrease in the duty cycle value is applied.

A swarm of particles, each symbolizing a possible solution, is produced by the method known as PSO. In addition to having a position and velocity, each particle evolves based on its previous position, its optimum location, as well as the optimum locations of its neighbours. The best answer is found as a result of this progression. Every iteration compares the value of the goal function with the optimal value, and every individual particle is aware of its

best visited position, best neighbour's position, and value [36-38].

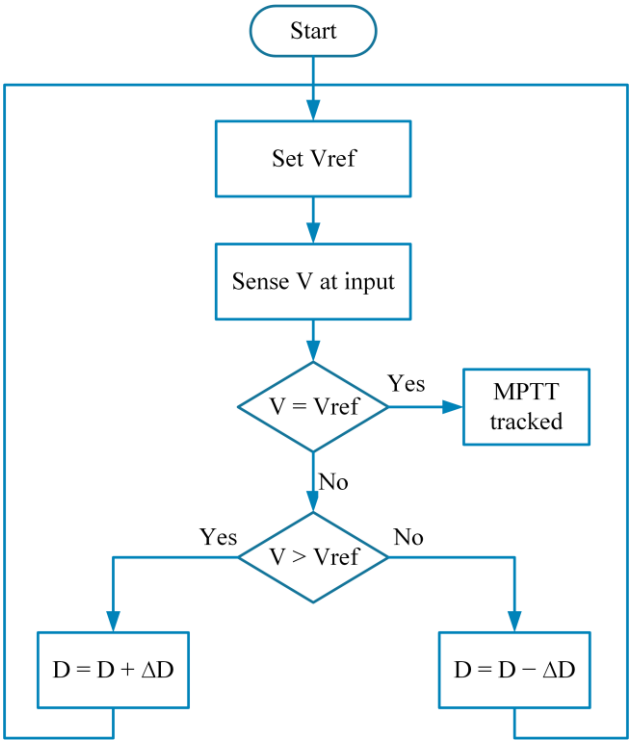


Figure 4. Flowchart of the CV MPPT method

Equation 12 shows the velocity function.

$$v_i^{t+1} = w \times v_i^t + c_1 \times r_1 \times (p_{best} - x_i^t) + c_2 \times r_2 \times (g_{best} - x_i^t) \quad (12)$$

Equation 13 shows the position function.

$$x_i^{t+1} = x_i^t + v_i^{t+1} \quad (13)$$

The CV and PSO MPPT approaches are combined into a single algorithm in this section of the study to generate a hybrid approach. The classical and simple CV algorithm is harmonized with the powerful and efficient PSO algorithm. In the algorithm, the CV algorithm first starts by generating a duty cycle. This generated duty cycle is then used with the power value in the PSO algorithm to create a more optimized duty cycle.

The CV-PSO hybrid MPPT algorithm is first initialized with the CV algorithm. In the first stage, the reference voltage is determined. In the second stage, the voltage of the PV array is measured. In the third stage, MPP tracking is completed when the measured V_{pv} equals the V_{ref} value. In the fourth stage, the duty cycle value is increased when the V_{pv} value is greater than the V_{ref} value, and decreased when it is not. In the fifth stage, the necessary parameter updates are made. The duty cycle, V_{pv}, and I_{pv} values are sent from this algorithm to the PSO algorithm.

In the PSO algorithm, the initial parameters and limits are determined in the first stage. Here, v represents particle speed values, x represents particle positions, and r_1, r_2 represent random coefficients.

In the second stage, the particle positions and speeds are set here. The particle positions represent the duty cycle values. The particle speeds determine how the duty cycle value will change at each step. The position and speed values are randomly determined within the bounded area.

In the third stage, the fitness value of each particle is determined. The power value obtained using voltage and current values is set as the fitness value. Each particle is matched with a suitable fitness value.

In the fourth stage, the fitness value obtained by each particle is compared with its own (personal) past best value (p_{best}). If the fitness value in the current step is greater than the p_{best} value, the particle's value is updated. Then, all p_{Best} values are sorted to determine the global best value (g_{best}). This value corresponds to the optimal duty cycle value.

In the fifth stage, the position and speed information of each particle is updated. This process is adjusted based on the distance of the particles from both the p_{best} and g_{best} values. Here, various values determined at the outset, such as the inertia weight (w), cognitive coefficient (c_1), and social coefficient (c_2), are taken into account.

In the sixth stage, if the required criteria are met, the g_{best} value is determined as the best duty cycle value. Furthermore, final updates are made based on whether the algorithm has reached a certain number of iterations and whether the threshold values have been reached.

The flowchart of the CV-PSO MPPT method is depicted in Figure 5.

2.3.1.3 *Hill climbing and particle swarm optimization MPPT*

In regard to the operating concept, the HC and the P&O are the same; the only distinction is the perturbation variable. The HC method modifies the duty cycle, while the P&O technique observes and modifies the current or voltage for MPPT. The main problem with both approaches is the compromise between dynamic reaction inaccuracy and constant state efficiency. This issue is more serious for the HC approach, as Figure 6 shows, it regulates the duty cycle (δ) rather than voltage [35, 39].

In this section, a hybrid algorithm is developed using the HC and PSO MPPT algorithms. The duty cycle generated in the HC algorithm is used as input to the PSO algorithm. The power and duty cycle values are evaluated in the PSO method to produce a corrected duty cycle.

In the HC algorithm, the first stage measures the voltage and current values of the PV array. In the second stage, the power value is calculated, and the difference between the previous power value and the current value (the power change value) is recorded. In the third stage, whether the power change value is greater than zero is examined. In the fourth stage, if the power change value is greater than zero, the duty cycle value is increased by a certain percentage. If it is less than or equal to zero, the duty cycle value is decreased. In the fifth stage, the final parameter update is performed. The generated duty cycle value, voltage, and current information are sent to the PSO algorithm. Finally,

the optimal duty cycle value is determined using these values in the PSO algorithm, the steps of which are described in Section 2.3.1.1.

The flowchart of the HC-PSO MPPT method is shown in Figure 7.

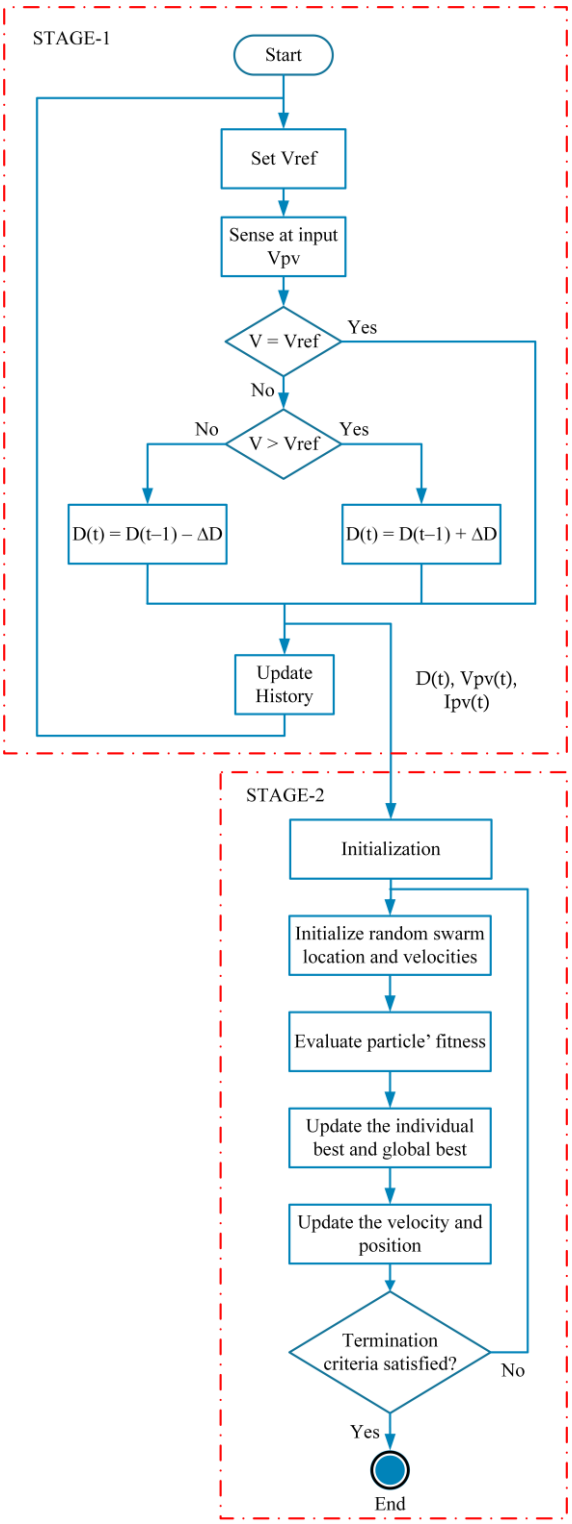


Figure 5. Flowchart of the CV and PSO hybrid MPPT method

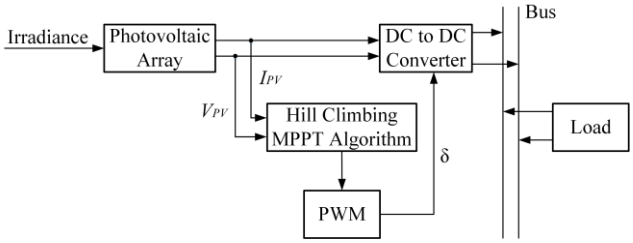


Figure 6. Hill climbing MPPT diagram

2.3.1.4 *Incremental conductance and particle swarm optimization MPPT*

Using the PV array's incremental and instantaneous conductance as a basis, the InC method is a common tracking technique. This approach is thought to be inexpensive and simple to use for MPPT. Although it uses a different check for perturbation, it uses the same fundamental concept as the P&O approach. The fluctuation around MPP and the poor rate of adaptation to rapidly varying air conditions are the two key drawbacks of the P&O approach. In order to prevent these drawbacks, this approach has been devised. The power and conductivity of solar panels are calculated by measuring their output current and voltage. The duty ratio needed to run the system at MPP is then calculated. The InC method is predicated upon the idea that the P-V curve's slope is zero, taking into account the convex feature of the P-V characteristic ($\Delta P/\Delta V = 0$). Figure 8 shows the flow diagram of the InC MPPT method [35, 40].

In the presented MPPT method, the InC-PSO MPPT methods are combined and hybridized. The duty cycle generated in the InC algorithm is used in the PSO algorithm, producing an improved, efficient duty cycle with increased power. In the InC algorithm, the first stage measures the voltage and current of the PV array.

In the second stage, the difference between the previous voltage value and the current value (voltage change value) is recorded. The same process is performed for the current value.

In the third stage, the voltage change value is checked for being greater than zero. If the voltage change value is greater than zero, the current change value is checked for being equal to zero. If this value is equal to zero, the algorithm stops. If not, the fourth stage is started. If the voltage change value is less than or equal to zero, the incremental conductance ($\Delta I/\Delta V$) and instantaneous conductance ($-I/V$) are examined for being equal. If they are equal, the algorithm stops; if not, the fourth stage is started.

In the fourth stage, if the current change value is not equal to zero, the current change value is examined for being greater than zero. If the incremental conductance ($\Delta I/\Delta V$) and instantaneous conductance ($-I/V$) values are not equal, the incremental conductance value is examined to determine whether it is greater than the instantaneous conductance value.

In the fifth step, if the current change value is greater than zero, the duty cycle value is increased; otherwise, it is decreased. If the incremental conductance value is greater

than the instantaneous conductance value, the duty cycle value is increased; otherwise, it is decreased.

In the sixth step, all parameters are updated, and the duty cycle, voltage, and current values are transmitted to the PSO algorithm.

Finally, the optimal duty cycle value is determined using these values in the PSO algorithm, the steps of which are outlined in Section 2.3.1.1. The flowchart of the InC-PSO MPPT is shown in Figure 9.

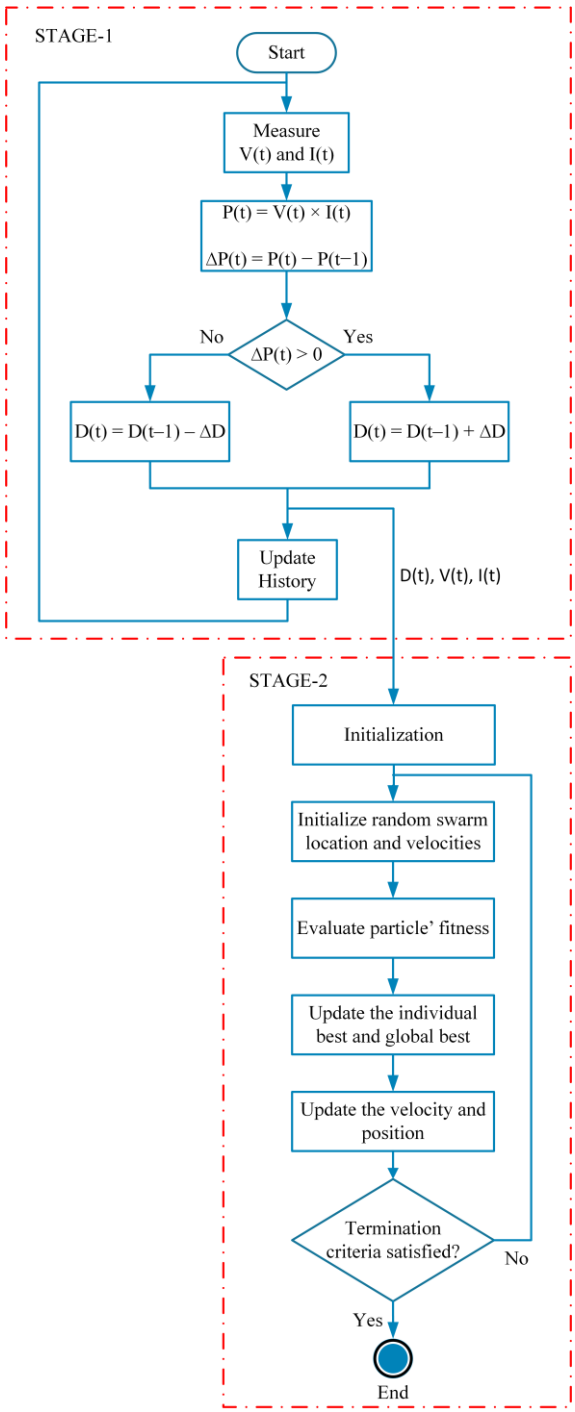


Figure 7. Flowchart of the HC-PSO hybrid MPPT method

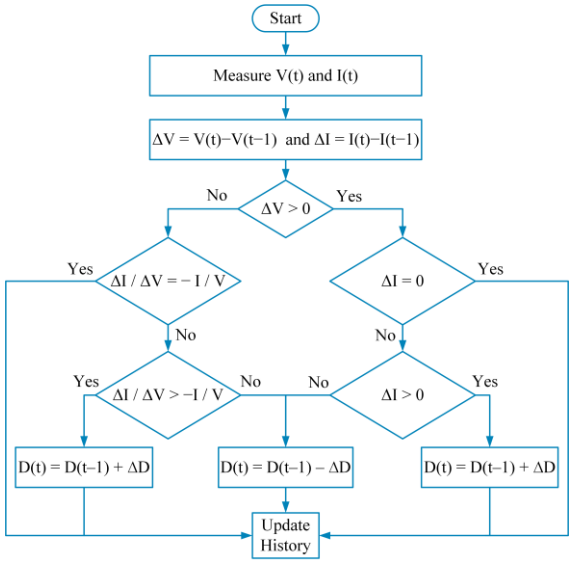


Figure 8. Schematic for the InC approach

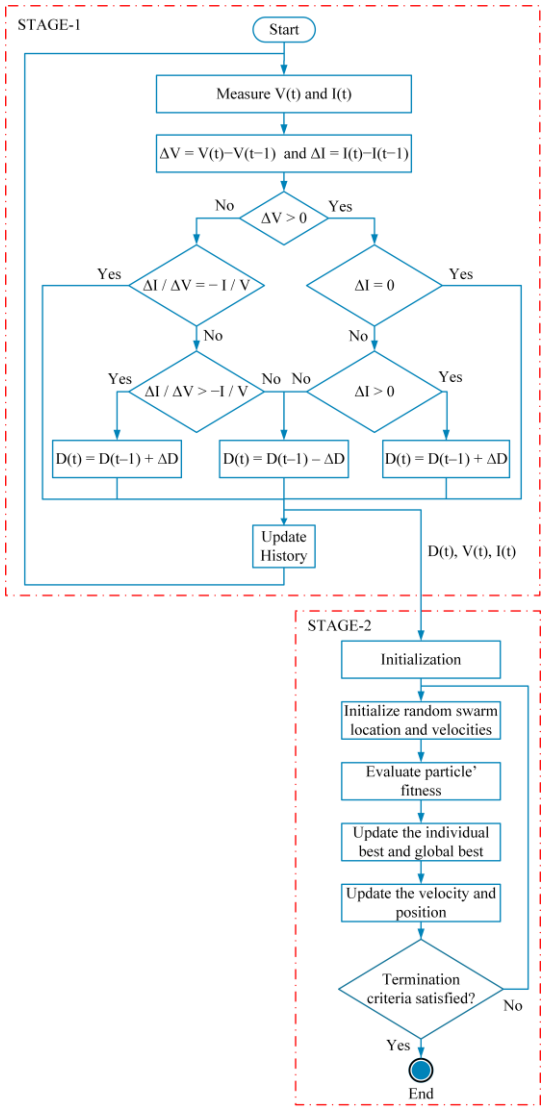


Figure 9. Flowchart of the InC-PSO hybrid MPPT method

2.3.1.5 *Partial shading scenario*

While testing the MPPT methods, a total of six irradiance levels have been prepared with irradiance levels of 1000 W/m^2, 700 W/m^2, 900 W/m^2, 800 W/m^2, 600 W/m^2, and 700 W/m^2, seriatim.

In the structure, irradiance data has been created with the signal builder and the block view is shown in Figure 10.

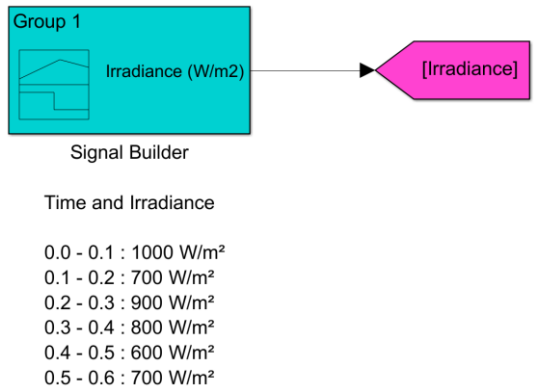


Figure 10. Signal builder block view containing irradiance data

The irradiance levels shown in Figure 11 vary randomly and sharply. By providing sharp irradiance transitions, rapid weather changes are simulated. This allows MPPT performance to be monitored under rapid and realistic conditions. The difference between the two changing irradiance levels has been set at 100 W/m^2, 200 W/m^2, and 300 W/m^2 to create various sudden changes. Abrupt changes in irradiance levels challenge MPPT methods, allowing for the analysis of power fluctuations and monitoring tracking accuracies.

The irradiance data representing the partial shading situation in the study and showing the irradiance changes are given in Figure 11.

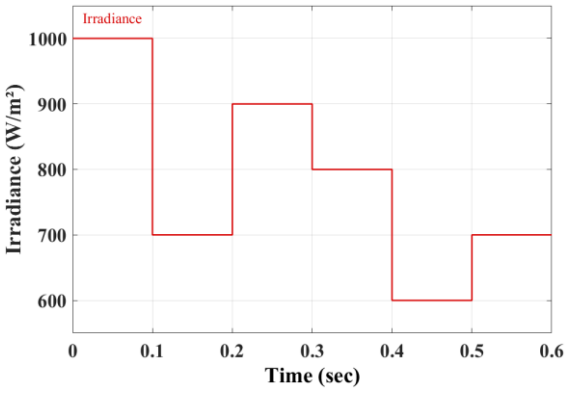


Figure 11. Graph of the solar irradiance values

3 Results and discussion

3.1 *Simulation results of constant voltage and particle swarm optimization MPPT*

This part shows the simulation results testing the CV-PSO MPPT. The following graphs show the converter output voltage and current, input and output power values, and the final duty cycle.

The output voltage graph of the CV and PSO hybrid MPPT method is depicted in Figure 12. In the CV-PSO MPPT algorithm, the converter output voltage exhibits excessive fluctuation behaviour during rapid irradiance changes.

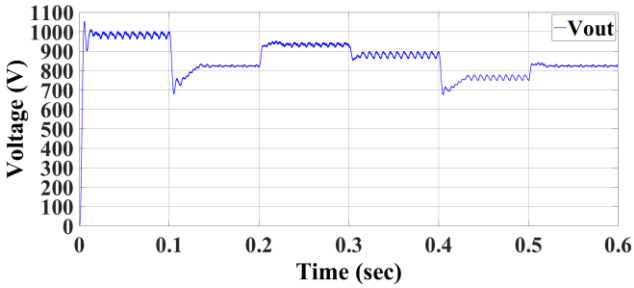


Figure 12. Converter output voltage graph of the CV-PSO MPPT

The output current of the CV and PSO hybrid MPPT method can be seen in Figure 13. Similarly, it is understood that the converter output current ripple is at a high level.

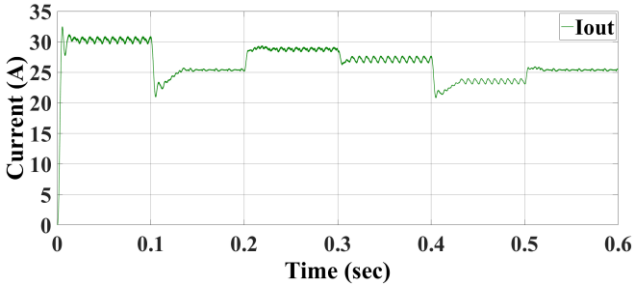


Figure 13. Converter output current graph of the CV-PSO MPPT

The input-output powers of the CV and PSO hybrid MPPT method are depicted in Figure 14. It is seen that the converter output power graph is the graph showing the most fluctuation.

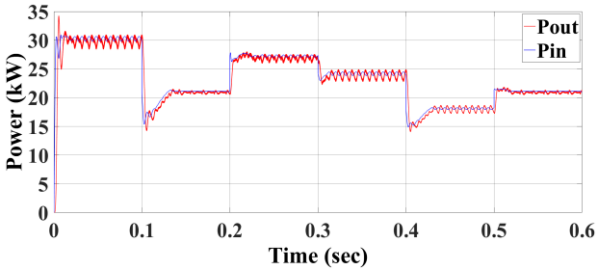


Figure 14. Converter input-output powers of the CV-PSO MPPT

The switching duty cycle graph of the CV-PSO MPPT is shown in Figure 15. As can be seen from the duty cycle ratio graph, the duty cycle fluctuation rate is also high.

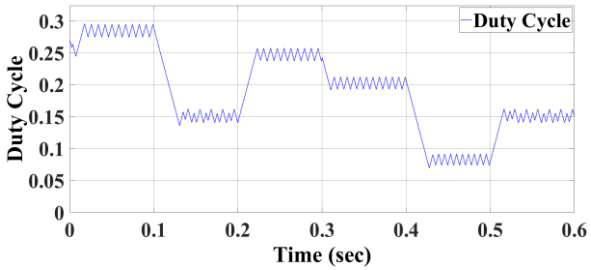


Figure 15. Converter switching duty cycle graph of the CV and PSO hybrid MPPT method

3.2 Hill climbing and particle swarm optimization MPPT

Results from simulations evaluating the HC and PSO hybrid MPPT approaches are displayed in this section. The DC-DC boost converter final duty cycle, input and output power levels, and output voltage and current are displayed in the accompanying graphs.

The output voltage graph of the HC-PSO MPPT is shown in Figure 16. In the HC-PSO MPPT algorithm, the converter output voltage performs much better than the CV-PSO algorithm during rapid irradiance changes.

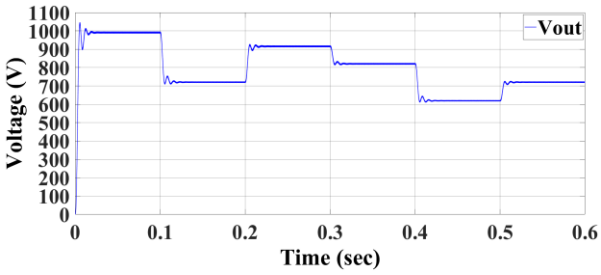


Figure 16. Converter output voltage graph of the HC-PSO MPPT

The output current of the HC-PSO MPPT is shown in Figure 17. In the current graph, a much better result is seen in terms of fluctuation compared to the CV-PSO method.

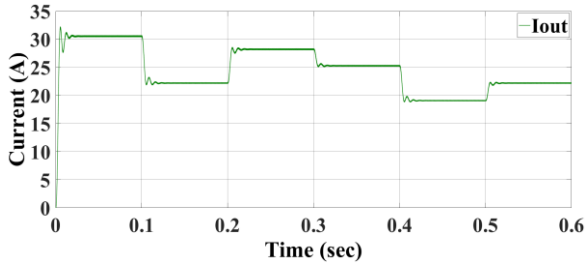


Figure 17. Converter output current graph of the HC-PSO MPPT

The input-output power graphs of the HC and PSO hybrid MPPT method are demonstrated in Figure 18. Although the maximum power level of the output power graph is lower than the CV-PSO algorithm, the power graph is found to be more stable.

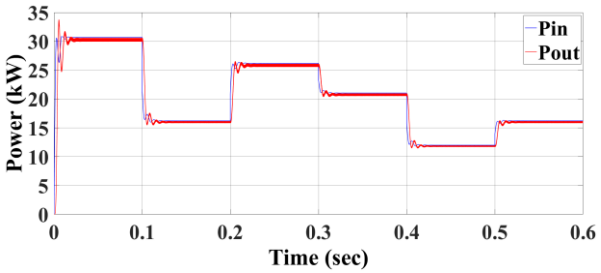


Figure 18. Converter input-output power graphs of the HC and PSO hybrid MPPT method

The switching duty cycle graph of the HC-PSO MPPT is shown in Figure 19. The duty cycle ratio graph shows high fluctuations at transition times. However, steady-state oscillations are found to be low.

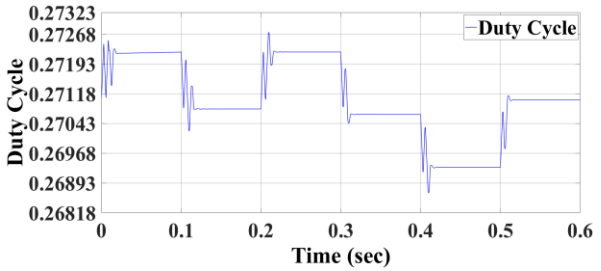


Figure 19. Converter switching duty cycle graph of the HC and PSO hybrid MPPT method

3.3 Simulation results of incremental conductance and particle swarm optimization MPPT

Within this results part, the simulation outputs of the proposed InC-PSO MPPT are examined. The output current and voltage, input and output power values, and final duty cycle of the DC-DC boost converter can be seen in the associated graphs.

The output voltage of the InC and PSO hybrid MPPT method is given in Figure 20. The voltage ripple in the converter output voltage graph is much less than with the CV-PSO algorithm. The amount of ripple is generally less than with the HC-PSO method, except for one transition point.

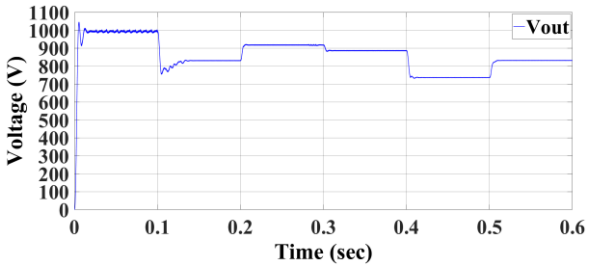


Figure 20. Converter output voltage graph of the InC-PSO MPPT

The output current graph of the InC-PSO MPPT is shown in Figure 21. Similar results are seen in the current graph as in the voltage graph.

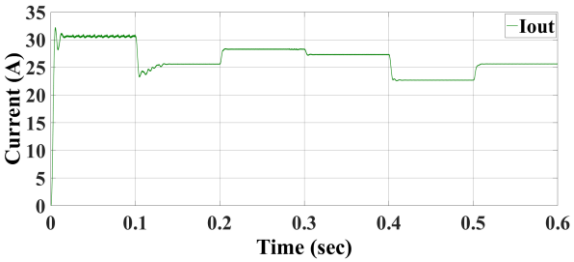


Figure 21. Converter output current graph of the InC-PSO MPPT

The input-output power of the InC-PSO MPPT is depicted in Figure 22. In the power graph, the method provides the best power generation at low irradiance levels compared to other methods.

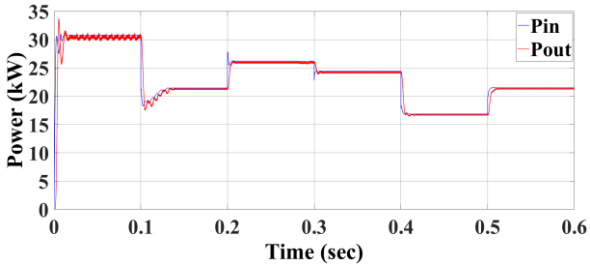


Figure 22. Converter input-output power graphs of the InC and PSO hybrid MPPT method

The switching duty cycle graph of the InC-PSO MPPT is shown in Figure 23. In the duty cycle graph, it is seen that the proposed method makes less oscillation in the duty cycle, and its accuracy is higher than other methods.

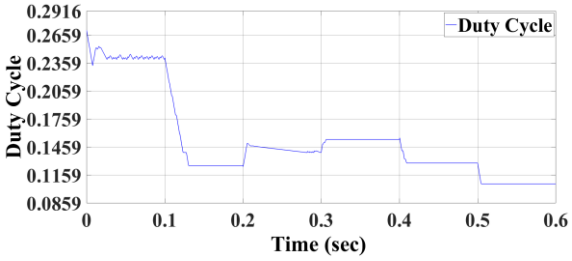


Figure 23. Converter switching duty cycle graph of the InC-PSO MPPT

3.4 Comparison of hybrid MPPT methods

This section interprets and compares the simulation results. All methods in the simulations have been tested in the same test scenario. Irradiance values of 1000 W/m², 700 W/m², 900 W/m², 800 W/m², 600 W/m², and 700 W/m² has been used in all simulations, respectively.

Comparative input-output power graphs of the CV-PSO, HC-PSO and InC-PSO hybrid MPPT methods are shown in Figure 24.

Comparative switching duty cycle graphs of the CV-PSO, HC-PSO and InC-PSO hybrid MPPT methods are shown in Figure 25

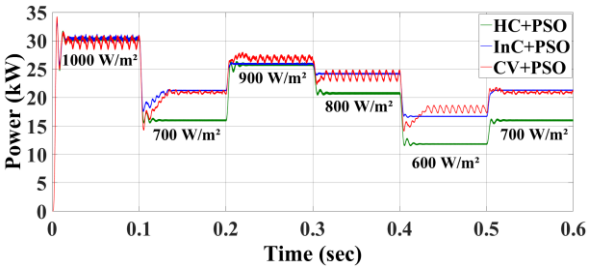


Figure 24. Comparative input-output power graphs of the CV-PSO, HC-PSO, and InC-PSO hybrid MPPT methods

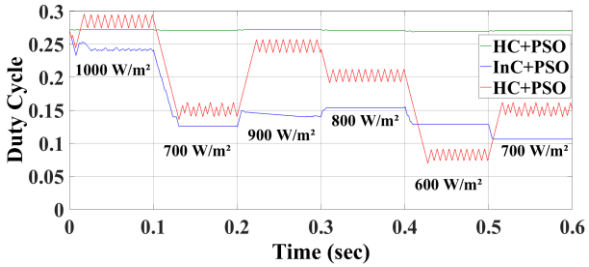


Figure 25. Comparative switching duty cycle graphs of the CV-PSO, HC-PSO, and InC-PSO hybrid MPPT methods

Simulation results show that while the CV and PSO MPPT methods provide higher peak power output than the others, the generated power output is fluctuating and unstable. Furthermore, the MPP tracking speed and response are lower than the other algorithms. Their simplicity and ease of implementation make them a preferred choice economically.

The HC and PSO MPPT methods exhibit a more stable and smoother power output in their power graphs. However, this algorithm failed to provide adequate MPP tracking at low irradiance levels.

In the proposed InC and PSO MPPT method, the DC-DC boost converter power output graph is generally more stable and exhibits less fluctuation. It has been determined that the compared hybrid methods provide higher power output, especially under low irradiance conditions.

Comparison of the CV-PSO, HC-PSO and InC-PSO hybrid MPPT methods is shown in Table 4.

Table 4. Simulation results and comparison of the hybrid MPPT methods

MPPT	Tracking Accuracy	Efficiency (%)	Avg. Power (kW)	Time to Reach MPP (sec.)	Power Ripple (kW)
InC-PSO	High	98.60	23.063	0.001	0.3
HC-PSO	Medium	98.29	19.996	0.029	0.5
CV-PSO	Low	98.48	23.039	0.035	1.6

When the tables and graphs in the results and discussion section are examined, it is concluded that the proposed MPPT technique is an efficient method when comparing tracking accuracy, efficiency, average output power, time to reach MPP, and power ripple.

4 Conclusions

Solar PV technology is increasingly popular today. Solar PV systems are highly susceptible to environmental factors. When PV cells do not receive sufficient irradiance, the power they produce will decrease. Partial shading is an example of this negative effect. MPPT methods are being developed to overcome partial shading. This work established a new hybrid MPPT approach based on Particle Swarm Optimization and Incremental Conductance. Simulations have been prepared for the proposed method, including the Constant Voltage-Particle Swarm Optimization Hybrid MPPT and the Hill Climbing-Particle Swarm Optimization Hybrid MPPT methods. The designed MPPT and the other method have been tested under varying irradiance conditions. The irradiance levels have been selected as 1000 W/m², 700 W/m², 900 W/m², 800 W/m², 600 W/m², and 700 W/m², respectively.

The findings of the simulation demonstrate that although the CV and PSO MPPT approaches provide higher peak power output than the others, the power output that is produced is unstable and varies. The MPP tracking speed and reaction are also slower than those of the other algorithms. They are a popular option economically due to their simplicity and ease of deployment. According to their power graphs, the HC and PSO MPPT approaches produce power production that is steadier and smoother. Nevertheless, at low irradiance levels, this method is unable to offer sufficient MPP monitoring. The DC-DC boost converter power output graph is often steadier and shows less variation in the proposed InC and PSO MPPT approach. This proposed hybrid approach has been found to provide more power, particularly in low-irradiance situations.

According to the simulation results, the limitations of the presented technique should be considered: the computational complexity and measurement errors of the InC algorithm should be considered as limiting factors. However, the computational overhead, hardware implementation difficulties, and parameter selection difficulties of the PSO method should be considered.

In this study, the performance of the proposed hybrid MPPT method is verified using the MATLAB/Simulink R2016b simulation environment. In future studies, a hardware-based experimental set will be prepared, and the proposed hybrid MPPT method will be tested in real-time and experimentally in a laboratory environment. Furthermore, the scope of the study can be expanded by comparing this method with different metaheuristic MPPT methods.

Conflict of interest

The authors declare no conflicts of interest.

Similarity rate (iThenticate): 15%

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