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RESEARCH ARTICLE

Advanced MPPT Control Algorithms: A Comparative Analysis of Conventional and Intelligent Techniques with Challenges

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ABSTRACT

Photovoltaic systems can be used for both off-grid and grid-connected applications. Solar systems use a smart technology called Maximum Power Point Tracker (MPPT) to squeeze the most power possible out of the sun. MPPT works by constantly fine-tuning the voltage from the solar panels using a special component (DC-DC converter) to ensure they operate at their peak efficiency This project offers a new analysis of MPPT along with the basic ways it responds to changing conditions. It examines how different DC-DC converter designs work with MPPT algorithms under various environmental factors. The project emphasizes the importance of choosing the right MPPT controller to ensure maximum power production from your solar system. It compares traditional MPPT algorithms used with different DC-DC converter topologies commonly found in solar energy systems. It also includes a technical comparison of these different approaches, focusing on factors like specific design elements, how quickly the system tracks changes in power output (tracking speed), and overall efficiency.

Keywords: DC-DC Converters, Intelligent MPPT algorithms, MPPT, Perturb and Observe.

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1. INTRODUCTION

As we fight climate change, solar energy is becoming increasingly popular. Scientists are looking for ways to replace dirty fuels with clean, renewable sources like sunshine. Solar cells capture sunlight and turn it into electricity. These cells are grouped into solar panels. To efficiently store solar power in batteries, solar systems often use a voltage regulator (DC-DC converter) to adjust the electricity from the panels. In some cases, an inverter is used to connect the system to the power grid and supply your home. For solar systems to work best, the voltage regulator needs to operate at its peak performance level. This is where a clever technology called Maximum Power Point Tracking (MPPT) comes in. MPPT constantly fine-tunes the regulator to ensure the system captures the most power possible from the sun. The performance of solar panels and how they work with the voltage regulator can be described by graphs. While some research has looked at the whole solar system, there's a gap in our knowledge. We need to compare different types of voltage regulators and digital controls to see which work best for solar applications. This study focuses on how well different voltage regulators work with traditional MPPT methods under various conditions, like temperature and sunlight levels [1]. By understanding this, we can design and improve solar systems to capture even more clean energy from the sun.

2. MATHEMATICAL MODELLING

This section delves into a mathematical model created to represent a specific solar panel, the ST090P (36). This model serves as a virtual tool to analyze and predict how the panel behaves under various environmental conditions, allowing us to optimize its energy output. The model is based on the following specifications of the ST090P (36) panel:

- *Maximum Power (Pmax)*: 85 Watts (W)—This denotes the maximum power output the panel can deliver under ideal conditions.
- *Maximum Voltage (Vmp)*: 17.6 Volts (V)—The voltage at the operational point where the panel produces its maximum power (Pmax).

- *Maximum Current (Imp)*: 5.11 Amps (A)—This is the current flowing through the panel at the operating point where it delivers its maximum power (Pmax).
- *Voc (Voc)*: 22.2 Volts (V)—This is the voltage measured across the panel's terminals when no current is flowing (open circuit).
- *Isc (Isc)*: 5.35 Amps (A)—This is the current flowing through the panel when its terminals are directly shorted (short circuit).

Unlike a light bulb, solar panels don't produce a constant amount of power. The amount of electricity they generate depends on how much sunlight they receive (irradiation) and how hot they are (temperature). These factors affect the voltage and current coming out of the panel, which we can see on special graphs called P-V and I-V curves [2] as shown in Fig. 1. The P-V curve shows how much power the panel produces at different voltages. It reaches a peak, which is the best operating point for the panel (called the Maximum Power Point or MPP). This point has specific voltage (Vmp) and current (Imp) values. The I-V curve shows the relationship between the current flowing through the panel and the voltage it produces. Two important points on this curve are Voc and the Isc. Understanding these curves is essential for predicting how much power a solar panel will generate under different conditions. The model also considers how weather affects these curves because sunshine and temperature can significantly change how much power a panel produces in Fig. 2.

Solar panel efficiency typically decreases as temperature rises. The model accounts for this effect, allowing us to predict how hotter environments will reduce the panel's power output. The amount of sunlight hitting the panel, or irradiance, directly affects its power generation. The model considers how varying irradiance levels will change the P-V curve, allowing us to estimate power output under different sunlight conditions. Shading a portion of the panel can significantly disrupt its overall power output. The model can be extended to simulate partial shading scenarios and predict the resulting decrease in efficiency [3]. By incorporating these environmental factors, the mathematical model becomes a powerful tool for designing and optimizing solar energy systems. We can use it to predict panel performance, select appropriate components, and maximize energy production under real-world operating conditions.

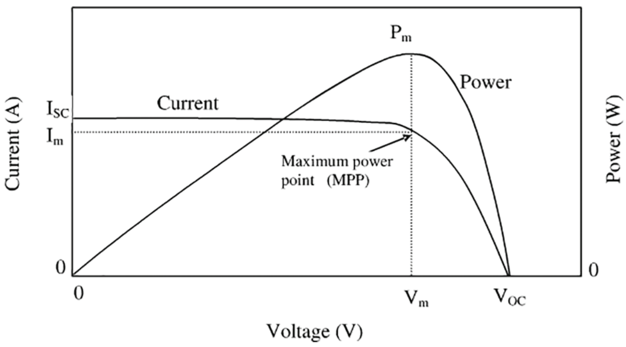

Fig. 1. IV-PV curves to track maximum power point.

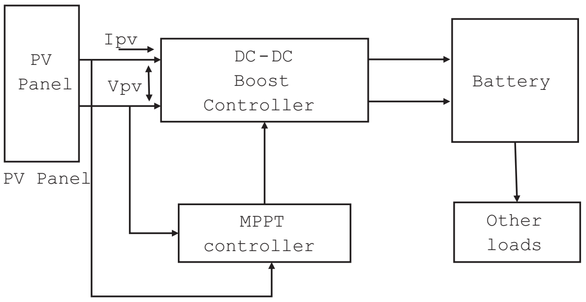

Fig. 2. Design flow of Solar MPPT charge controller.

2.1. *Modelling of a PV Cell*

Solar cells convert sunlight into electricity by a well-established phenomenon. When light particles (photons) hit the solar cell material, they can knock loose electrons, creating an electric current [4]. This process relies on a special structure within the cell called a p-n junction. Several techniques exist to explain and predict a solar cell's behavior under various conditions. This study builds upon a model that simplifies the solar cell as an individual diode. This approach offers a reliable balance between accuracy and complexity, allowing researchers to solve the circuit using a technique called the Lambert-W function (LWF). The core of this model lies in the following equation, which describes the current flow within the solar cell.

The equation essentially states that the total current (I) is the sum of the photocurrent (Iph) generated by sunlight, the current through the diode (Id), and the current through the shunt resistor (Is). The current through the diode and the thermal voltage are influenced by the cell's temperature and a parameter called the ideality factor, which accounts for non-idealities in real-world solar cells. By analyzing this equation and the factors that influence its components, researchers can gain valuable insights into how solar cells operate under different conditions. This knowledge is crucial for designing and optimizing solar energy systems for efficient power generation.

2.2. *Model of a PV Panel*

Individual solar cells are like building blocks for creating larger solar panels or arrays. These solar arrays are the workhorses that collect a lot of sunlight and turn it into electricity we can use. To maximize efficiency and meet specific power requirements, solar cells can be strategically connected in various configurations. This section delves into two fundamental connection methods, series, and parallel connections.

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s\frac{N_s}{N_p}}{nV_TN_s}\right) - 1\right] - \frac{V + \frac{N_s}{N_p}R_sI}{\frac{N_s}{N_p}R_p}$$

Imagine connecting solar cells in series like stacking batteries. Each cell acts as a separate voltage source, and their individual voltages add up. This technique is particularly advantageous when the goal is to achieve a higher overall voltage output at the array level. The resulting series connection is suitable for applications requiring higher voltage, such as powering DC appliances directly. Connecting solar cells in parallel is analogous to connecting wires in parallel [5]. In this configuration, the current produced by each cell flows through its own independent path. Consequently, the total current output of the array increases proportionally to the number of parallel connections. This method is ideal for scenarios where higher current is needed, without affecting the overall voltage output. For instance, parallel connections might be used to power appliances with high current demands.

The true power of solar cell connections lies in their versatility. By cleverly combining series and parallel connections, we can design a solar array customized to meet specific voltage and current requirements. El- Sebah et al. provides a more in-depth exploration of these configurations. The optimal amount of cells linked in series (N_s) and parallel (N_p) depends on several factors, including the target voltage and current needed for the application, as well as the available space and the electrical limitations of the system's components. For example, if we need to power a DC motor requiring a specific voltage but have limited space constraints, connecting the cells in series might be the preferred approach [6]. Conversely, if the application demands a high current to power multiple appliances and space is not a major concern, a parallel connection strategy might be more suitable.

3. DC-DC Converters

In photovoltaic (PV) systems, maximizing power generation is crucial. This is where (MPPT) comes in, ensuring the solar panels function at their finest power production under variable ecological specifications. However, the voltage delivered by solar panels doesn't always perfectly match the needs of battery storage or connected appliances. This is where DC-DC converters play a vital role. A DC-DC converter is an electronic circuit that efficiently transforms a DC voltage from one level to another [7]. With MPPT solar systems, these converters are the workhorses behind the scenes. They tirelessly fine-tune the voltage coming from the solar panels, ensuring it's ideal for charging batteries or powering various devices. By strategically selecting and configuring a DC-DC converter, we can unlock the full potential of our solar panels and ensure efficient energy utilization. The world of DC-DC converters offers a variety of choices, each with unique characteristics and functionalities.

Buck Converter (Step-Down Converter) excels at reducing the input voltage ($V_o < V_s$). It's the perfect choice when the solar panel voltage needs to be lowered for safe and efficient battery charging or powering low-voltage appliances. Imagine a scenario where your solar panels generate 22 volts, but your battery bank is designed for 16 volts. A buck converter steps down the voltage to prevent damage and ensure optimal charging. In contrast to the Buck, the Boost converter elevates the input voltage ($V_o \geq V_s$). This becomes crucial when powering devices with higher voltage requirements than the solar panels can directly provide. For instance, if your solar panels produce 14 volts, but a specific appliance you want to operate needs 50 volts, a boost converter bridges the voltage gap, allowing you to utilize the solar energy for that device. Buck-Boost Converter (Step-Up/Down Converter) is a versatile converter that presents the expert of equally creations. It can function as a buck converter ($0 < D < 0.5$) for voltages lower than the input or transform into a boost converter ($0.5 < D < 1$) for voltages higher than the input. This flexibility makes it an asset in systems with varying voltage demands [8].

Exploring the design considerations for each converter type. It provides sample calculations for specific scenarios, allowing readers to understand the thought process behind selecting appropriate component values. Input Voltage (Vs) signifies the voltage supplied by the solar panel under specific operating conditions. Output Voltage (Vo) is the desired voltage level we aim to achieve after conversion, suitable for battery charging or powering specific devices. Input Current (I) signifies the current flowing from the solar panel, which is an essential factor for determining component ratings within the converter. Duty Cycle (D) impactful parameter represents the ratio of the switch's on-time to its on-and-off cycle time within the converter. By adjusting the duty cycle, we significantly influence the output voltage. Switching Frequency (f) refers to the frequency at which the converter's switch turns on and off. This frequency plays a role in factors like efficiency and component selection [9]. Inductor (L) and Capacitor (C) are essential components within the DC-DC converter circuit as depicted in Fig. 3. The inductor helps regulate current flow, while the capacitor helps smooth out voltage variations, ensuring stable operation.

For a Buck Converter, the design prioritizes ensuring continuous inductor current for stable operation. Additionally, capacitor selection focuses on minimizing the output voltage ripple, keeping the voltage delivered to the battery or device as steady as possible. Like the buck converter, continuous inductor current is maintained for stability, and capacitor selection targets low output voltage ripple for clean power delivery in the Boost converters.

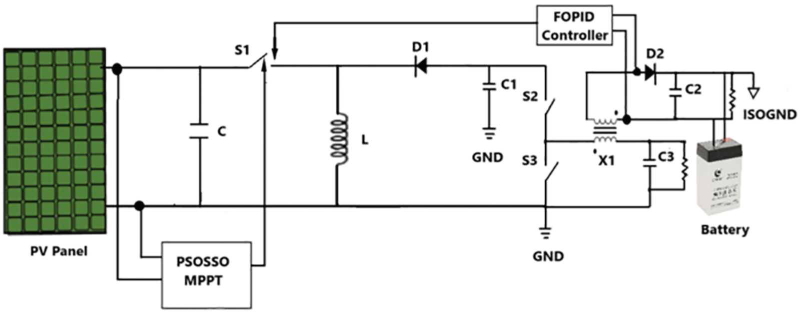

Fig. 3. Solar MPPT charge controller with DC-DC converter.

The duty cycle plays a central role in the Buck-Boost Converter, dictating its step-up or step-down behavior. Considerations include maintaining continuous inductor current and controlling output voltage ripple for optimal performance. Cuk Converter offers the additional ability to invert the output voltage polarity related to the input voltage. The design process involves calculating average inductor currents to determine appropriate component values for efficient operation. Like the Cuk converter, the SEPIC converter offers reversed output polarity. The design ensures continuous converter operation, minimizing input current ripple for better efficiency. Capacitor selection considers output voltage ripple, inductor saturation prevention.

4. MPPT Controller

In the ever-evolving world of solar energy, squeezing every watt of potential out of your panels is crucial. This is where MPPT technology steps in as a silent hero, constantly working behind the scenes to ensure your solar system operates at its absolute best. Imagine your solar panels as a dynamic terrain–a landscape with constantly shifting hills and valleys. These variations represent the impact of environmental factors like temperature, sunlight intensity (irradiance), and even partial shading. Nestled somewhere in this ever-changing landscape lies a critical point at MPP [10]. This is the sweet spot where your solar panels deliver their maximum power output. The MPP isn't static. As the sun's position changes all through the day and environmental factors fluctuate, the MPP on this solar power landscape constantly moves. Here's where MPPT technology comes into play. It acts like a sophisticated climber, tirelessly searching for the peak on this ever-shifting terrain.

MPPT controllers are the brains behind the operation. They continuously monitor the current and voltage output of the solar panels. By comparing these values with pre-set references (voltage, current, or power), the MPPT controller makes intelligent decisions. In solar systems with MPPT, a special device called a controller plays a critical role. It's connected to a voltage regulator (DC-DC converter) that acts like a switch, constantly adjusting the electricity coming from the solar panels. This ensures the voltage is perfect for charging batteries or powering appliances.

The controller is like a smart switch, constantly fine-tuning how long the "switch" is on (duty cycle) to find the ideal operating point for the solar panels (MPP). This is the point where the panels produce the most power. By doing this, the system squeezes the maximum amount of usable energy from the sunlight. But just finding the MPP isn't enough. To be truly effective, the MPPT controller needs some extra features, which we'll explore next. When environmental conditions change rapidly, like a sudden cloud passing over the panels, the MPPT controller needs to react quickly. A fast response time minimizes any power loss during these transitions, ensuring smooth operation and maximizing overall energy production. Imagine the climber constantly teetering on the peak – that's not ideal for an MPPT controller. A well-designed controller should maintain a steady operation at the MPP, avoiding oscillations that could lead to power fluctuations. Not all peaks are created equal. The MPPT controller should have the ability to distinguish between minor fluctuations and the true global MPP, the absolute highest point on the power landscape. This precision translates to maximizing efficiency and extracting the most power possible under any given conditions. Time is of the essence when it comes to solar energy. The faster the MPPT controller can locate the MPP under changing conditions, the less potential power is lost. A high tracking speed ensures the system quickly adapts to variations and captures the maximum available energy. Ultimately, the goal of MPPT is to squeeze the most power out of your solar panels. A well-designed MPPT controller, with its fast response, stability, precision, and tracking speed, paves the way for a highly efficient solar system, maximizing the return on your investment in solar energy.

4.1. Conventional MPPT Algorithms

Conventional techniques offer a good balance between complexity and performance, making them suitable for many solar PV applications. However, they may not be ideal for scenarios with rapidly changing weather conditions or partial shading, where newer AI-powered or metaheuristic approaches might be more effective.

4.1.1. P&O (Perturb and Observe)

One popular way to find the MPP (the point where solar panels produce the most power) is a method called P&O algorithm in MPPT. The P&O algorithm starts by slightly increasing or decreasing the voltage coming from the solar panels (using the DC-DC converter). Then, it measures how much power the panels are producing after the change [11]. If the power output improves while increasing the voltage, the algorithm keeps raising the voltage a little more. This suggests we're getting closer to the MPP, where power is highest. If the power output goes down after increasing the voltage, the algorithm reverses direction and starts decreasing the voltage [12]. This means we've passed the MPP and need to adjust back towards it. By constantly making these small adjustments and observing the power output, the P&O algorithm can find the MPP and keep the solar panels operating at their peak performance as shown in Fig. 4.

4.1.2. IC (Incremental Conductance) Algorithm

The Incremental Conductance (IC) algorithm is a extensively used technique for MPPT in photovoltaic (PV) systems. It offers several advantages compared to simpler algorithms like (P&O), making it a popular choice for efficient solar power generation.

At the core of the IC algorithm lies the concept of instantaneous conductance. This value represents the tilt of the P-V curve of the solar panel at a particular operating point. It's calculated by Instantaneous Conductance (dI/dV). The IC algorithm then compares this instantaneous conductance with the voltage (V) of the solar panel [13]. This comparison helps determine the direction towards the MPP. Based on the comparison, the system adjusts the operating voltage of the PV system through the DC-DC converter's duty cycle like in Fig. 5.

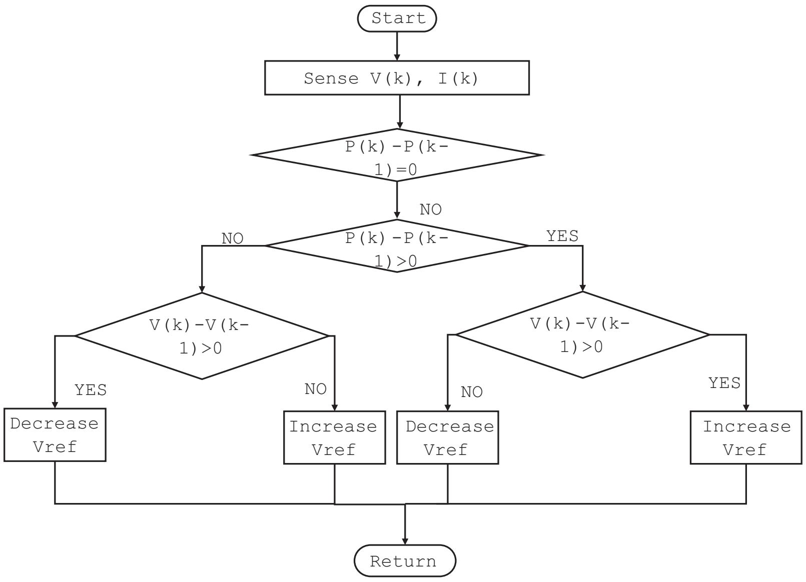

Fig. 4. P&O algorithm in MPPT charge controller.

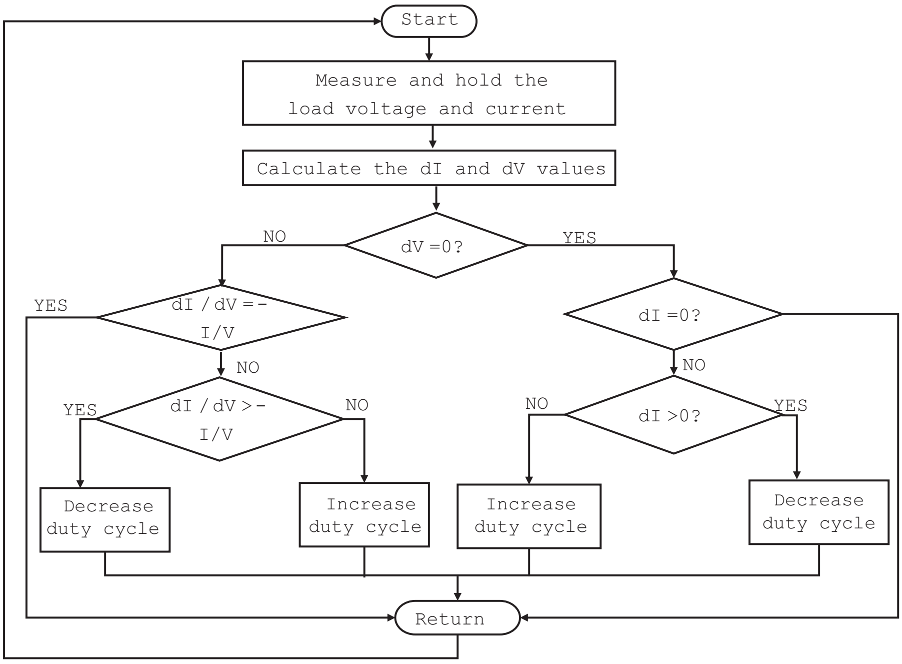

Fig. 5. IC algorithm in MPPT charge controller.

The Incremental Conductance (IC) algorithm is another approach to finding the MPP (the point where solar panels produce the most power). Comparing the rate of change in current (dI) to the change in voltage (dV). It compares how much the current changes (dI) when the voltage changes slightly (dV). This tells the algorithm if it's moving up or down the power curve. If the current increases more than the voltage increase (dI > V), the algorithm knows it's to the left of the MPP on the power curve [14]. So, it slightly increases the voltage (using the DC-DC converter) to move closer to the MPP. As the voltage goes up, the current change usually slows down, eventually matching the voltage at the MPP. If the current increases less than the voltage increase (dI < V), the algorithm knows it's to the right of the MPP. So, it slightly decreases the voltage to move closer to the MPP. As the voltage goes down, the current change usually increases, again bringing it in line with the voltage at the MPP [15]. By constantly monitoring this relationship between current change and voltage change, the IC algorithm can find the MPP and keep the solar panels operating at their peak performance.

This process of calculating instantaneous conductance, comparing it with voltage, and adjusting the operating voltage is a continuous cycle. The IC algorithm constantly monitors the system's behavior and makes real-time adjustments to maintain operation close to the MPP. Compared to P&O, the IC algorithm exhibits less oscillation around the MPP. This is because the comparison with voltage provides more specific direction for adjustments, leading to smoother operation and potentially higher efficiency. By minimizing oscillations, the IC algorithm allows the system to operate closer to the true MPP for longer durations, potentially resulting in higher overall power output compared to P&O, especially under rapidly changing environmental conditions. While offering advantages over P&O, the IC algorithm remains relatively simple to implement compared to more complex MPPT techniques like Artificial Neural Networks (ANN). The accuracy of the IC algorithm can be affected by noise present in the system's measurements of voltage and current. This might lead to inaccurate calculations of instantaneous conductance and potentially hinder optimal tracking. In scenarios with partial shading on the solar panels, the IC algorithm might struggle to identify the true global MPP, potentially leading to suboptimal performance. Overall, the IC algorithm offers a good balance between simplicity, efficiency, and performance, making it a popular choice for MPPT in many solar power systems [16]. However, for specific applications where noise reduction techniques or advanced MPP identification under partial shading are crucial, other MPPT algorithms like those based on ANNs might be explored.

4.1.3. Pulse Width Modulation for MPPT

PWM is a widely used technique for controlling power in various electronic circuits. In the context of PV systems, it can be employed for a basic form of MPPT. However, it's important to understand its limitations compared to dedicated MPPT algorithms. PWM operates by regulating the duty cycle of a switching signal. Imagine a square wave, where the on-time (pulse width) is a fraction of the total cycle time (period) [17]. By adjusting this duty cycle, PWM effectively controls the average voltage delivered to a load. In an MPPT scenario, the load is typically the battery being charged by the solar panel like in Fig. 6.

The system keeps a close eye on the voltage coming from the solar panels. It compares this voltage to a special value, like a target, that's chosen to be close to the MPP (the point where the panels produce the most power). Based on this comparison, the controller adjusts. It controls a special switch linked between the panels and the battery [18]. This switch works by turning on and off fast. The controller determines how long the switch stays on during each cycle (duty cycle). By altering the duty cycle, the controller can fine-tune the voltage coming from the solar panels to match the target voltage, which is close to the MPP [19]. This ensures the panels operate at their peak performance and delivering the most power possible. If the panel voltage is lower than the reference, the duty cycle might be increased to allow more current to flow and potentially raise the voltage towards the MPP [20]. Conversely, if the panel voltage is higher than the reference, the duty cycle might be decreased to limit current flow and potentially reduce the voltage back closer to the MPP [20].

The assumption of a fixed reference voltage as a proxy for the MPP is a significant drawback. The MPP voltage varies depending on environmental factors like temperature and irradiance (sunlight intensity). This static approach can lead to significant deviations from the true MPP, resulting in power losses. Due to the constant adjustments and potential operation away from the true MPP, PWM-based MPPT often sacrifices efficiency compared to dedicated MPPT algorithms like P&O or IC. While PWM offers a simple and low-cost solution, its effectiveness is diminished in applications demanding high efficiency or operating under rapidly changing environmental conditions [21].

Despite its limitations, PWM-based MPPT might be a suitable choice for specific scenarios. In applications where budget constraints are paramount, and maximizing every watt of power generation isn't critical, the simplicity

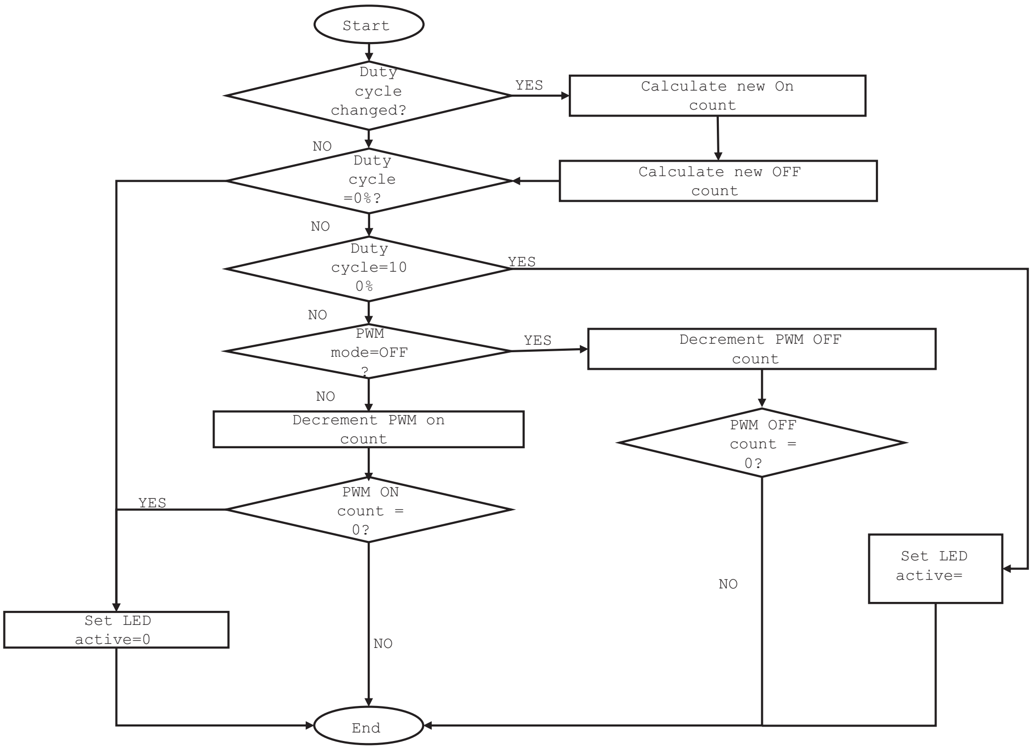

Fig. 6. PWM algorithm in MPPT charge controller.

and low cost of PWM can be appealing. For very small-scale PV systems with minimal power requirements, the potential efficiency losses associated with PWM might be less significant.

4.1.4. *Fractional V_{oc} and I_{sc}*

Fractional V_{oc} and I_{sc} present themselves as attractive options for designing an MPPT system in PV applications. Their appeal lies in their inherent simplicity, making them particularly suitable for specific scenarios. However, it's crucial to acknowledge the trade-offs involved when employing these methods to ensure they align with project requirements [22]. The FOCV method hinges on the principle of estimating the MPP voltage (VMPP) by multiplying V_{oc} of the PV panel with a coefficient factor (Kfocv). This factor typically falls within the range of 0.70 to 0.85, and its precise value depends on the specific characteristics of the PV panel being used as depicted in Fig. 7.

V_{oc} stands out for its ease of implementation. It requires minimal calculations and doesn't necessitate any complex hardware components, making it an attractive choice for cost-conscious projects. Due to the absence of intricate components, the overall design based on the V_{oc} method translates to lower upfront costs. This can be a significant advantage for applications where budget constraints are paramount [23].

The constant factor approach inherent to V_{oc} can introduce a degree of inaccuracy. The assumption that a fixed ratio consistently reflects the actual MPP voltage under varying environmental conditions like temperature and irradiance isn't always valid. This potential discrepancy can lead to suboptimal power output from the PV system, failing to capture the maximum potential energy generation. The V_{oc} method suffers from limited adaptability. The constant factor doesn't account for the characteristics of the PV panel changing over time due to factors like aging or degradation [24]. As the panel ages, its efficiency can decline, and the once-optimal Kfocv value might no longer yield the true MPP.

Like V_{oc}, the I_{sc} method estimates a value related to the MPP. In this case, the focus shifts to the MPP current (IMPP), which is estimated by multiplying the I_{sc} of the PV panel with a constant factor (K_{fsc}). As with K_{focv}, this factor typically ranges from 0.70 to 0.85. I_{sc} inherits the same advantages of simplicity and low cost as FOCV, making it another attractive option for budget-driven projects [25]. Like V_{oc} and I_{sc} suffers from limitations in accuracy due to its reliance on constant factor estimation. Additionally, the method's inherent challenge lies in accurately measuring the I_{sc}. This value isn't always readily available in all PV systems, and obtaining it can be a complex process, further hindering the method's effectiveness [26]. Due to the requirement for I_{sc} measurement, I_{sc} might not be universally applicable across all PV system designs as shown in Fig. 8.

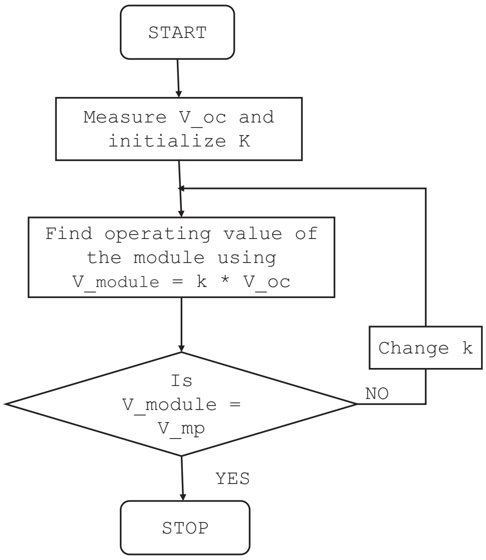

Fig. 7. V_{oc} algorithm in MPPT charge controller.

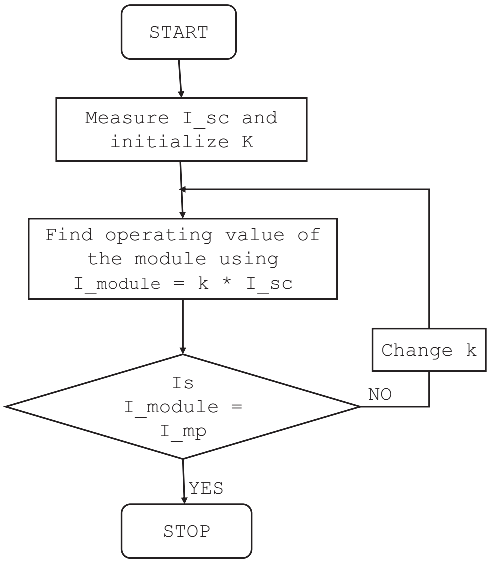

Fig. 8. I_{sc} algorithm in MPPT charge controller.

While V_{oc} and I_{sc} offer a basic approach to MPPT design, incorporating some additional considerations can enhance their effectiveness. Choosing the appropriate constant factor (Kfocv or Kfsc) is critical for maximizing accuracy. Ideally, the factor should be based on the specific PV panel datasheet or obtained through meticulous experimental measurements under controlled conditions. Although these methods don't actively track the MPP, monitoring environmental conditions like temperature can provide valuable insights [27]. By incorporating temperature correction factors into the calculations, the estimated MPP voltage or current can be adjusted to improve accuracy, partially mitigating the limitations of the constant factor approach.

For projects with tight budgetary limitations, the low-cost implementation and design simplicity offered by V_{oc} and I_{sc} make them strong contenders. In scenarios where maximizing every watt of power generation isn't essential, the potential trade-off in accuracy with these methods might be acceptable. If the PV system operates in an environment with minimal fluctuations in temperature and irradiance, the constant factor approach might be less prone to errors, making V_{oc} or I_{sc} more viable options.

4.1.5. *Hill Climb (HC) MPPT Algorithm*

HC mimics the act of climbing a hill. It continuously adjusts the operating voltage (or duty cycle of a power

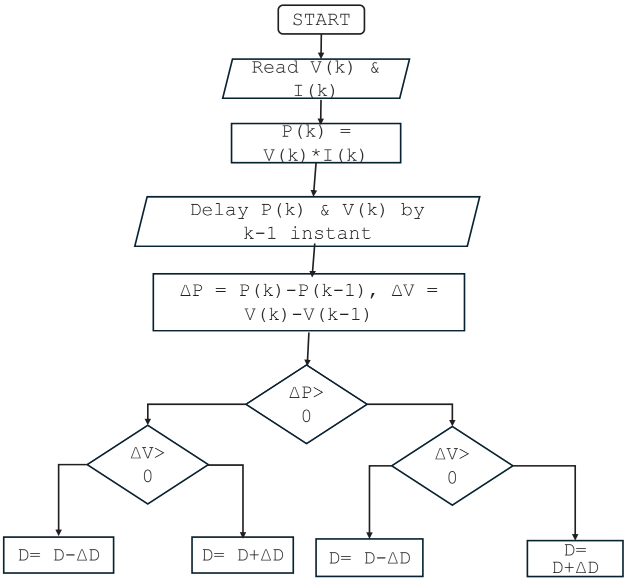

Fig. 9. HC algorithm in MPPT charge controller.

converter) of the PV array and monitors the corresponding change in power output. The algorithm moves in the direction that leads to an increase in power, ultimately converging towards the MPP on the P-V curve of the solar panel [28]. The system starts with an initial operating voltage (Vo) on the P-V curve. A small voltage step (ΔV) is added or subtracted to the current operating voltage (Vo). This can be either a positive or negative step depending on the chosen implementation. The power output (Po) of the PV array at the new voltage (Vo ± ΔV) is measured. The new power output (Po) is compared to the previous power output (Pp) at Vo.

1. If the new Po is larger than the previous Pp (i.e., moving uphill).
2. The algorithm keeps the change and updates the operating voltage (Vo) to the new value (Vo ± ΔV).
3. If the new power (Po) is less than the previous power (Pp) (i.e., moving downhill).
4. The algorithm discards the change and keeps the previous operating voltage (Vo).

Steps 2–4 are repeated continuously. The size of the voltage step (ΔV) can be fixed or adjusted dynamically based on the system's convergence speed. Can get stuck in local maxima if there's partial shading on the PV array (multiple peaks on the P-V curve). careful selection of the voltage step size (ΔV) to balance convergence speed and oscillations around the MPP is required. May not perform well under rapidly changing weather conditions due to its iterative nature. Overall, the HC MPPT algorithm is a good choice for applications where simplicity and cost are primary concerns [29]. However, for systems with partial shading or dynamic weather patterns, more advanced MPPT techniques might be needed like in Fig. 9.

4.2. *Intelligent MPPT Control Techniques*

In the relentless pursuit of maximizing energy harvest from PV systems, MPPT algorithms play a pivotal role. While conventional methods like Fractional V_{oc} and I_{sc} offer a balance between simplicity and affordability, they can fall short when dealing with complex operating environments or demanding peak efficiency requirements. Intelligent MPPT control techniques are a new wave of MPPT algorithms that leverage computational power to achieve higher efficiency and adaptability compared to conventional methods. Intelligent MPPT techniques incorporate elements of artificial intelligence (AI) or machine learning to learn and adapt to the constantly changing characteristics of a solar PV system. This can include factors like, Variations in solar irradiance, Changes in ambient temperature, Partial shading on the PV array [30]. These techniques can also handle complex system dynamics and non-linearities that traditional methods might struggle with.

4.2.1. *Artificial Neural Networks (ANNs)*

ANNs borrow inspiration from the structure and function of the human brain. These intricate networks consist of interconnected processing units, akin to artificial neurons. The true magic lies in their ability to learn and adapt. Through a rigorous training process, ANNs are exposed to vast datasets encompassing diverse environmental conditions (temperature, irradiance) and corresponding MPP values specific to the PV panel being used [31]. By meticulously analyzing these patterns, the ANN establishes complex relationships within the data. This newfound knowledge empowers the ANN to predict the MPP with exceptional accuracy, even under rapidly changing environmental conditions as depicted in Fig. 10.

Properly trained ANNs excel at pinpointing the MPP with unmatched precision, irrespective of fluctuating environmental conditions [32]. This translates to maximized power output from the PV system, ensuring the most efficient conversion of solar energy into electricity. As PV panels age, their characteristics can subtly change, impacting their performance. ANNs, with their inherent learning capabilities, can continuously adapt to these changes [33]. By being retrained with updated data collected over time, the MPPT system maintains its peak efficiency throughout the operational lifespan of the PV panel. Real-world

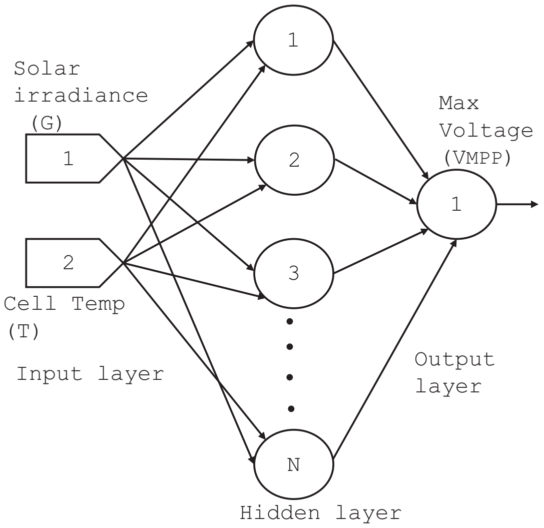

Fig. 10. ANN algorithm in MPPT charge controller.

scenarios often involve partial shading on the PV panels. This non-uniform distribution of sunlight creates multiple local maxima on the P-V curve, making it challenging to identify the true global MPP, the point of maximum power generation. ANNs, having been trained on diverse data sets that might include partial shading conditions, can effectively navigate these complexities [34]. They can decipher the intricate patterns within the data and identify the true global MPP, maximizing power output even under challenging shading patterns.

Implementing ANNs necessitates more processing power compared to simpler MPPT algorithms. This can translate to the need for more powerful and potentially costlier hardware, depending on the specific application. The complexity of the ANN architecture and the volume of data it needs to process are key factors influencing computational requirements. The accuracy and effectiveness of ANNs are heavily reliant on the quality and comprehensiveness of the training data used. Insufficient or inaccurate data can lead to suboptimal performance. Gathering high-quality, representative data that encompasses various operating conditions can be a challenge, and the training process itself can be computationally expensive.

4.2.2. *Fuzzy Logic Control (FLC): A Rule-Based Approach to MPPT*

FLC operates based on a set of predefined rules established by human experts, incorporating their knowledge, and understanding of PV system behavior. These rules translate system parameters like voltage, current, and temperature into fuzzy logic variables. Fuzzy logic allows for the representation of imprecise or non-categorical data, enabling the MPPT controller to make decisions based on these nuanced values.

FLC rules can be tailored to accommodate specific PV panel characteristics and system requirements. This offers a high degree of flexibility in the design process, allowing engineers to create an MPPT system that caters to the unique needs of the application. Like ANNs, FLC can be designed with rules to account for partial shading conditions [35]. By incorporating expert knowledge on how partial shading affects system behavior, the FLC system can be equipped to make informed decisions and improve MPPT performance under non-uniform irradiance. Compared to ANNs, FLC generally requires less computational power, making it a potentially suitable option for applications with hardware limitations or cost constraints. The simpler rule-based approach of FLC translates to lower processing demands as shown in Fig. 11.

Defining effective fuzzy logic rules necessitates substantial expertise in PV system behavior and control theory. This can be a barrier for some engineers who might lack the necessary knowledge or experience in fuzzy logic concepts. Developing a comprehensive set of rules often requires an iterative process of testing and refinement [36]. Optimizing the performance of FLC often involves an iterative process of rule adjustment and testing. This can be time-consuming and require ongoing effort, especially as operating conditions, or system configurations change. Unlike ANNs, which can potentially self-adapt through.

4.2.3. *Metaheuristic Algorithms for MPPT Control*

These are a powerful class of intelligent MPPT techniques inspired by natural phenomena. Unlike traditional methods that follow a fixed set of rules, these algorithms employ a more iterative and stochastic (random) approach to search for the MPP on the P-V curve of a solar panel. Metaheuristic algorithms mimic natural processes like Swarm intelligence (e.g., Particle Swarm Optimization (PSO), Evolutionary processes e.g., Genetic Algorithm (GA), Physical phenomena) [37]. These algorithms maintain a population of potential solutions like functional points on the P-V curve and iteratively improve them based on a fitness function, usually the power output.

Several optimization techniques inspired by biological processes can be employed to locate the MPP on the solar panel's (P-V) curve. These algorithms, such as GA and

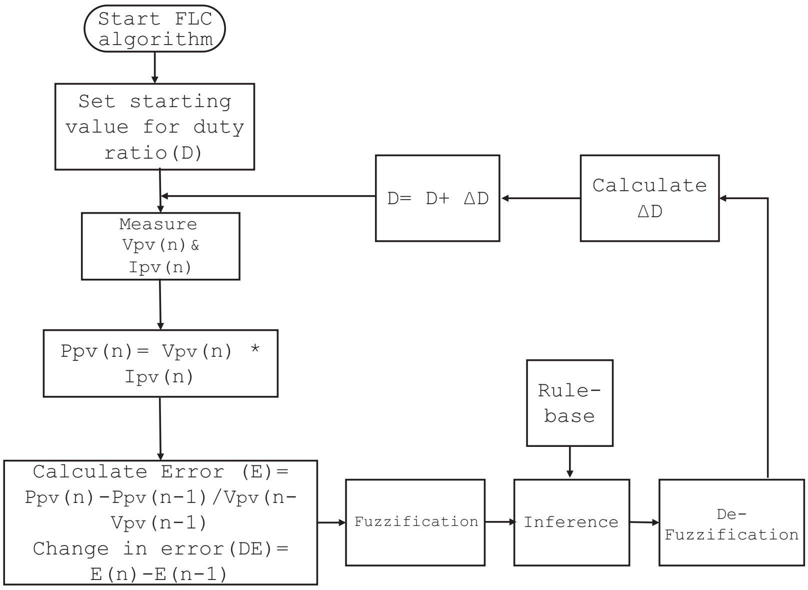

Fig. 11. FLC algorithm in MPPT charge controller.

PSO, operate iteratively to converge on the MPP. The process begins by generating an initial population of random operating points distributed across the P-V curve. Each point's power output is then evaluated, serving as a fitness function. This fitness function guides the selection of "superior" solutions–operating points with higher power output—for further exploration.

Drawing inspiration from natural phenomena, the algorithm modifies the existing population based on the chosen "superior" solutions. GA, for instance, utilizes mutation to introduce controlled variations, while PSO employs velocity updates to guide the exploration process. These modifications aim to generate new operating points with potentially even higher power output. Subsequently, "inferior" solutions with lower power output are replaced by the newly generated points. This iterative process of selection, modification, and replacement continues until a predefined stopping criterion is met. This criterion can be reaching a highest number of repetitions or identifying a solution with a power output exceeding a specified threshold, indicative of the MPP. By leveraging these bio-inspired algorithms, the system can efficiently search the P-V curve and converge on the operating point that maximizes power generation from the solar panels. This approach offers a robust and adaptable method for MPP tracking under adapting ecological conditions.

These processes can effectively search for the absolute MPP, even under partial shading, where multiple local maxima exist on the P-V curve. Some metaheuristic algorithms can locate the MPP quickly, minimizing power losses during transients. They can handle complex system dynamics and non-linearities, making them suitable for various operating conditions. These algorithms require more processing power compared to conventional methods. The performance of these algorithms depends on the modest selection of control constraints, which can be challenging [38].

4.2.3.1. Particle Swarm Optimization (PSO) in MPPT

PSO is a swarm intelligence (SI) practice increasingly employed in MPPT applications. Stimulated by the collective foraging behavior of social insects, PSO effectively locates the MPP on the P-V curve of a solar panel. This approach proves particularly advantageous under challenging environmental conditions, such as partial shading. The PSO algorithm operates iteratively. Initially, a population of elements has random distribution across the P-V curve. Each particle represents a potential operating point for the solar panel. The power output associated with each particle's position is calculated based on the P-V curve [39].

Throughout the iterative process, each particle retains a memorial of its personal greatest position (the point with the highest power output it has encountered) and the global best position discovered by the whole swarm. This information guides the movement of the elements towards favorable regions of the search space. Particle velocities are dynamically adjusted based on their current positions, memories of the best positions, and a stochastic component. These updated velocities determine the movement of the particles on the P-V curve in subsequent iterations.

The iterative process continues until a predefined stopping criterion is met. This criterion can be reaching a maximum number of repetitions or identifying a solution with a power output exceeding a specified threshold, indicative of the MPP. By leveraging the collective intelligence of the swarm, PSO efficiently navigates the P-V curve and converges on the MPP [40]. This bio-inspired approach offers a robust and adaptable strategy for MPPT under diverse environmental conditions, ensuring optimal power generation from solar panels like in Fig. 12.

Unlike some conventional methods, SI algorithms can efficiently search for the global MPP, even when the P-V curve has multiple peaks due to partial shading. PSO can locate the MPP relatively quickly, minimizing power losses during transients. They can handle complex system dynamics and non-linearities present in real-world solar PV systems.

Overall, swarm intelligence offers a powerful approach to MPPT, particularly for systems with partial shading or dynamic weather conditions. By mimicking the collective intelligence of nature, these algorithms can effectively navigate the complexities of solar power generation and maximize energy harvest.

4.2.3.2. Genetic Algorithms (GAs)

These are another form of metaheuristic algorithms used in MPPT that leverage the theories of spontaneous selection and progression. GAs mimics the process of biological evolution to find optimal solutions. In MPPT, the "solution" is the operating voltage (or duty cycle) that corresponds to the MPP. A population of potential solutions (voltage points) evolves over generations, with fitter solutions (those closer to the MPP with higher power output) having a higher chance of contributing to the next generation.

A population of chromosomes (strings representing voltage values) is randomly generated within the operational voltage range of the PV system. The power output is measured for each voltage point (chromosome) in the population. This power output serves as the fitness score for that solution. Based on the fitness score, a selection process chooses chromosomes with higher power output (more likely to be near the MPP) for reproduction [40]. Selected chromosomes undergo crossover, where parts of their genetic code (voltage values) are exchanged to create new offspring (combinations of potentially good solutions). A small random mutation is introduced into some offspring's chromosomes to maintain diversity and prevent premature convergence. The new offspring replace the least fit members (low power output) of the current population. Steps 2-6 are repeated for multiple generations. Over time, the population evolves towards chromosomes with higher fitness scores, converging on the voltage that leads to the MPP [41].

Like other metaheuristic approaches, GAs can effectively search for the absolute MPP, even under limited shading where there might be numerous local maxima on the P-V curve. They can handle variations in weather conditions and system dynamics by continuously evolving the population towards optimal solutions. Compared to traditional MPPT methods, GAs require more processing

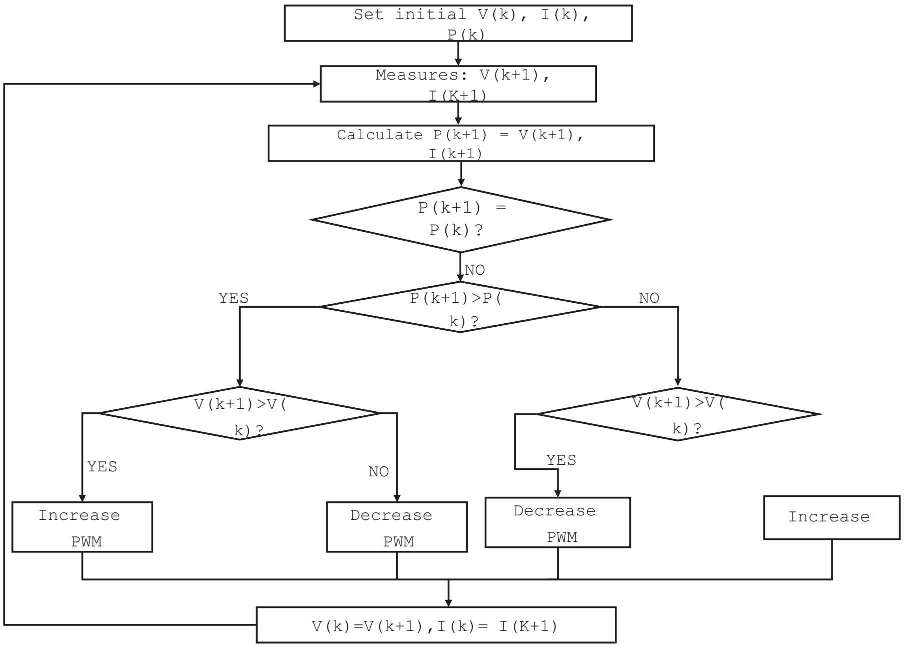

Fig. 12. PSO algorithm in MPPT charge controller.

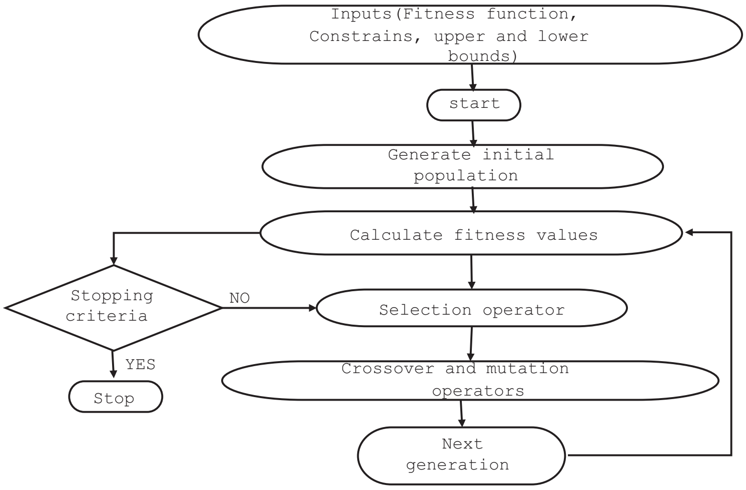

Fig. 13. GA algorithm in MPPT charge controller.

power due to the iterative nature and population manipulation. The performance of GAs depends on selecting appropriate parameters like population size, crossover rate, and mutation probability. Overall, Genetic Algorithms offer a robust MPPT technique for solar PV systems. By mimicking natural selection, GAs can efficiently search for the MPP and adapt to changing conditions, maximizing power generation. However, their computational demands need to be considered when choosing an MPPT strategy as depicted in Fig. 13.

4.2.3.3. Grey Wolf Optimization (GWO) in MPPT

GWO is a relatively new and powerful metaheuristic procedure used in MPPT that depicts inspiration from the social hunting behavior of grey wolves. GWO divides the virtual wolf pack into four levels based on dominance: Alpha, Beta, Delta, and Omega. These wolves represent different stages of the hunt for the prey (MPP) on the P-V curve. Alpha, the fittest wolf, corresponding to the solution closest to the MPP (highest power output). Beta, the second-best wolf, helps Alpha during the hunt and guiding the search. Delta, the third-best wolf, supports Alpha and Beta by providing information. Omega, the remaining wolves, exploring the search space for promising areas.

A population of "wolves" (potential operating points) is randomly distributed across the P-V curve. Each wolf's position represents a voltage value. The power output of each wolf is calculated, signifying its fitness level. The higher the power output, the fitter the wolf (closer to the MPP) [41]. The wolves with the top three highest fitness values are identified as Alpha, Beta, and Delta, respectively. The positions of Alpha, Beta, and Delta are used to guide the search towards the MPP. Omega wolves adjust their positions by encircling the supposed prey location based on:

1. D = |X_p(t) – X(t)| (Distance between prey and each wolf)

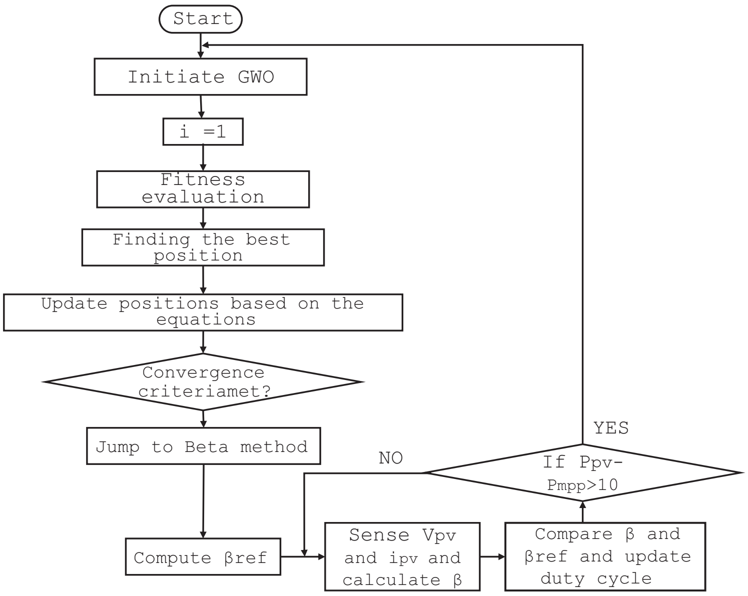

Fig. 14. GWO algorithm in MPPT charge controller.

2. X(t + 1) = X_p(t) − A ∗ D(t) (New position of each wolf)
    - X_p(t)–Position of Alpha, Beta, or Delta
    - X(t)–Current position of the wolf
    - A–Randomly decreasing coefficient to control convergence speed

A hunting strategy is simulated using a random weight (W) between 0 and 1 to balance exploration and exploitation: X(t + 1) = |X_p(t) − AWD(t)| (Updated position with random weight). Omega wolves update their positions based on the encircling and hunting strategies. Steps 2–6 are repeated. Over time, the pack converges towards the Alpha wolf's position, which represents the MPP like in Fig. 14.

GWO excels at finding the global MPP, even under partial shading with multiple local maxima on the P-V curve. The hunting and encircling strategies can efficiently guide the search towards the MPP, minimizing power loss during transients. Compared to some GAs, GWO requires fewer parameters to tune, simplifying implementation [42]. Overall, Grey Wolf Optimization offers a promising approach to MPPT for solar PV systems. By mimicking the cooperative hunting behavior of wolves, GWO can effectively navigate the complexities of the P-V curve and maximize power generation under various operating conditions [43].

Overall, metaheuristic algorithms are a valuable addition to the MPPT toolbox, offering significant for expanding power extraction from solar PV systems under complex and dynamic circumstances. As computational resources become more affordable, these techniques are poised to play an increasingly important role in future solar power generation.

5. Challenges in MPPT Control: Conventional vs. Intelligent

The quest for ever-increasing efficiency in solar power generation has driven innovation in Maximum Power Point Tracking (MPPT) controllers. While conventional MPPT techniques have served as the workhorses of the industry for years, intelligent controllers are emerging as a powerful new approach. Here is a deeper look at the challenges faced by each type of controller, along with the potential advantages of intelligent control. The comparison of different parameters of MPPT control algorithms are presented in Table I.

5.1. *Conventional MPPT Challenges*

The P&O and IncCond MPPT methods, while popular, are not ideal for situations where solar panels are partially shaded. Partial shading creates multiple high points on the power output curve, and these techniques can get stuck on a less significant high point rather than finding the absolute best one (GMPP). This leads to a reduction in the amount of energy collected.

Conventional techniques often require multiple adjustments to the operating voltage before reaching the MPP. This iterative process can be slow, especially under rapidly changing weather conditions like passing clouds. The delay in converging on the MPP translates to lost potential power generation during these transients.

Conventional MPPT controllers are designed with a specific set of assumptions about system behavior. They may not perform well when faced with complex system dynamics, such as variations in temperature or aging effects on solar panels. This can lead to suboptimal power output over time.

5.2. *Intelligent MPPT Challenges*

Intelligent controllers, particularly those utilizing metaheuristic algorithms or machine learning, often involve more complex calculations compared to conventional methods [44]. This can necessitate more powerful hardware

TABLE I: Comparison of Different Parameters MPPT Algorithm Techniques

MPPT algorithm	Sensed parameters	Dependency on PV array	Direct/ Indirect	Analog/ Digital	Efficiency	Response/ Speed	Cost	Complexity on implementation
P&O	Voltage, current	No	Direct	Both	Low	Varies	Low	Low
Incremental Conductance	Voltage, current	No	Direct	Digital	Medium	Varies	Low	Medium
Voc	Voltage	Yes	Indirect	Both	Low	Medium	Low	Low
Isc	Current	Yes	Indirect	Both	Medium	Medium	Low	Medium
Neural networks	Varies	Yes	Indirect	Digital	High	Fast	High	High
Fuzzy logic	Voltage, current	Yes	Direct	Digital	High	Fast	High	Medium

and sophisticated software, potentially adding cost and complexity to the system design.

Running complex algorithms requires processing power, which translates to energy consumption by the MPPT controller itself [45]. While the goal is to maximize overall power generation, the controller's energy usage needs to be factored in to ensure a net gain in efficiency.

Some intelligent techniques, like Genetic Algorithms (GAs), rely on carefully chosen control parameters to achieve optimal performance [46]. Selecting the right parameters can be a challenge, requiring expertise and potentially iterative testing for specific system configurations.

Machine learning-based MPPT controllers can be very powerful, but they often require training data specific to the solar PV system they are controlling. Gathering sufficient and representative data that accounts for various operating conditions can be an obstacle, especially for large-scale solar farms with unique layouts or environmental factors [47].

Intelligent algorithms like (PSO) and (GWO) excel at navigating the complexities of the P-V curve under partial shading. They can effectively search for the absolute MPP, ensuring the controller operates at the point of maximum power output regardless of shading patterns. Some intelligent techniques like PSO can locate the MPP very quickly by analyzing the search space more efficiently [48]. This minimizes power losses during transients, where rapid changes in irradiance (sunlight intensity) can cause the MPP to shift on the P-V curve. Intelligent controllers are designed to be more adaptable to various operating conditions. They can handle non-linearities in system behavior and adjust their control strategies based on real-time data. This allows them to maintain optimal performance under dynamic weather patterns, temperature fluctuations, and even potential degradation effects on solar panels over time.

Intelligent controllers open doors for optimizing not just power output but also other crucial factors in solar energy generation [49]. By incorporating algorithms that consider battery health in solar-plus-storage systems or inverter efficiency curves, intelligent MPPT can contribute to a more holistic approach to maximizing usable power and system longevity. The integration of machine learning into MPPT systems can pave the way for real-time fault detection and diagnosis. By analyzing operational data and historical trends, intelligent controllers might be able to identify early signs of equipment degradation or potential failures within the MPPT system or the connected solar panels [50]. This allows for preventive maintenance, reducing downtime and confirming the long-term consistency and operation of the entire solar power generation system.

6. FUTURE SCOPE

The field of intelligent control for MPPT is a rapidly evolving area with a lot of ongoing research focused on overcoming limitations and pushing the boundaries of efficiency in solar power generation. Here is a deeper dive into some key areas of research, exploring not just the focus areas but also potential challenges and future directions:

- The quest for ever-more-efficient MPPT algorithms continues. Researchers are exploring new metaheuristic algorithms inspired by a wider range of natural phenomena. For instance, algorithms mimicking animal foraging behavior (e.g., Harris Hawks Optimization) or biological processes like bacterial foraging (Bacterial Foraging Optimization) are being investigated for their potential to outperform existing methods.
- Research is ongoing into combining different metaheuristic techniques or integrating them with established MPPT methods like (P&O) or (IncCond). This hybridization can leverage the strengths of each approach, potentially leading to faster convergence, improved efficiency under dynamic conditions, and better global MPP tracking under partial shading. Additionally, research into dynamically adapting the control parameters of these algorithms based on real-time operating conditions is crucial for optimizing performance across diverse environments.
- Machine learning, particularly reinforcement learning, holds immense promise for MPPT. Reinforcement learning algorithms can be trained through simulation or real-world data to learn optimal control strategies for the MPPT system under various operating conditions. This data-driven approach can potentially outperform pre-programmed algorithms by continuously adapting to changing system dynamics and environmental factors.
- A critical challenge in incorporating machine learning into MPPT is ensuring the algorithms can learn and adapt online, meaning they can adjust their behavior in real-time based on new data. Additionally, research on "explainable AI" is necessary to

understand the decision-making processes of these algorithms, fostering trust and enabling further refinement.

The future of solar power generation lies in its integration with smart grids. Here, research is focused on developing intelligent MPPT controllers that can communicate with smart grid systems. While intelligent control algorithms offer significant advantages, they can also add complexity to the MPPT system. Research is underway to explore new hardware platforms and low-power computing techniques that can efficiently execute these algorithms. This ensures that the benefits of intelligent MPPT outweigh the additional processing power requirements, especially for resource-constrained solar PV systems. Traditionally, MPPT algorithms have focused solely on maximizing power output. However, research is now exploring multi-objective optimization techniques. By optimizing for these multiple objectives, researchers aim to develop a more holistic approach to MPPT that ensures not only maximum power generation but also system longevity and operational efficiency.

The integration of AI and machine learning into MPPT systems opens doors for real-time fault detection and diagnosis. By analyzing operational data and historical trends, these intelligent systems can potentially identify early signs of equipment degradation or potential failures within the MPPT system or the connected solar panels. This allows for preventive maintenance, reducing downtime and guaranteeing the long-term consistency of the solar power generation system.

These are just a few of the exciting areas of research in intelligent control for MPPT. As the field progresses, we can expect even more sophisticated algorithms, hardware advancements, and machine learning techniques that will play a crucial role in maximizing solar energy harvest, optimizing grid integration, and ensuring a clean and sustainable future.

7. Conclusion

Intelligent MPPT controllers, leveraging metaheuristic algorithms, machine learning, or a combination of both, offer a powerful alternative. These techniques excel at overcoming the challenges faced by conventional methods. However, intelligent MPPT also comes with its own set of challenges, including increased complexity, computational burden, and the need for careful parameter tuning or training data for machine learning approaches. Looking ahead, the future of MPPT lies in intelligent control. As hardware efficiency improves, algorithms become more sophisticated, and research progresses in areas like multi-objective optimization and proactive maintenance, intelligent MPPT controllers will play a key role in maximizing solar energy generation, optimizing grid integration, and ensuring a clean and sustainable energy future. This review has highlighted the strengths and weaknesses of both conventional and intelligent MPPT techniques. By understanding these trade-offs, engineers can select the most suitable MPPT controller for a specific solar PV system, considering factors like complexity, cost, operating conditions, and desired level of efficiency. With continued research and development, intelligent MPPT controllers are poised to revolutionize the way we harvest solar energy.

Conflict of Interest

Authors declare that they do not have any conflict of interest.

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