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MPPT Algorithms for Partial Shading of Solar PV Cells

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ABSTRACT

The photovoltaic (PV) system directly converts solar radiation into electricity using solar cells, typically composed of semiconductor materials. The I-V (current-voltage) characteristics of the PV system exhibit nonlinearity, influenced by factors like temperature and sunlight intensity. Within the I-V curve, there exists a singular operating point known as the Maximum Power Point (MPP). The MPP represents the optimal conditions for power production, and it can shift based on environmental variations. To enhance efficiency, Maximum Power Point Tracking (MPPT) algorithms are commonly employed. These algorithms continuously adjust the system's operating point to ensure it operates near the MPP, thereby optimizing power output under changing conditions. The Maximum Power Point (MPP) is susceptible to fluctuations due to alterations in electrical demand and meteorological factors. To optimize the efficiency of the solar PV system, the Maximum Power Point Tracker (MPPT) is employed to continuously monitor and adjust to the MPP. Various strategies for MPPT and their implementation are extensively discussed in the literature. This work aims to provide an extensive overview of different MPPT methods under partial shade and uniform insolation conditions.

Keywords: Solar Photovoltaic, nonlinearity, meteorological factors, Maximum Power Point Tracking, Partial Shading, uniform insolation, Optimal technique, control strategy.

1. INTRODUCTION

The growing daily demand for energy, combined with the depletion of conventional energy sources, has led governments and energy organizations worldwide to seek clean and renewable alternatives. Among these options, photovoltaic energy is particularly promising. It is a clean, abundant, noiseless, and readily available energy source, making it increasingly utilized in various applications. Due to the increasing affordability of solar PV panels and the improving efficiency of power electronics circuits, there is a rising demand for both grid-connected and standalone PV systems. Despite these advancements, it's important to note that even the most efficient PV panels currently exhibit a conversion efficiency ranging from 11% to 28%. Moreover, without proper maintenance, this efficiency can further decrease over time. There exists a singular point where the power available is optimal for any given combination of temperature and irradiance in a photovoltaic system. This critical point is known as the maximum power point (MPP), and the technique employed to ensure a photovoltaic system operates at this MPP is termed Maximum Power Point Tracking (MPPT). **[2]**

To optimize power extraction, it is essential to implement an efficient Maximum Power Point Tracking (MPPT) technique that performs well across a range of environmental conditions. Various strategies and circuit design approaches have been documented in the literature, all aimed at enhancing the efficiency of photovoltaic (PV) systems. While there is a wealth of technical literature covering various MPPT approaches, the majority of review papers have traditionally focused on methods applicable under normal radiation conditions. This study distinguishes itself by presenting significant and practical MPPT strategies, going beyond standard MPPT systems. It also explores MPPT approaches under partial shading conditions to optimize the efficiency of PV systems. This review study provides researchers and practitioners with guidelines for selecting the optimal MPPT control scheme among the various technologies available. The current emphasis in research is on further improving the efficiency of solar photovoltaic systems by enhancing the extraction of power from photovoltaic cells. The principal limitation of solar photovoltaic systems arises from the variability in output voltage due to fluctuations in temperature and insolation. The process of adjusting the operating point of a photovoltaic (PV) array to track its Maximum Power Point (MPP) is termed Maximum Power Point Tracking (MPPT). The primary objective of MPPT approaches is to identify the voltage (VMPP) or current (IMPP) at which a photovoltaic plant should operate to attain the maximum power output (MPPP) under defined temperature and irradiance conditions. The complexity of a solar installation's P-V (power-voltage) performance increases notably, displaying multiple peaks when subjected to partial shading. There are currently several MPPT monitoring approaches in use, and research suggests evaluating the majority of these techniques by comparing them to the power collected from photovoltaic panels. The two predominant MPPT algorithms, Perturb and Observe (P&O) and Incremental Conductance (IC), are widely employed. The author conducts an evaluation and analysis of the energy extraction percentages, considering both scenarios with and without the implementation of MPPT. Several types of Maximum Power Point Tracking (MPPT) have been developed and introduced. When it comes to determining the Maximum Power Point (MPP) of a solar panel with a combination of stability and a high response rate, fuzzy logic stands out as one of the optimal choices. Recent documentation has further emphasized MPPT research, highlighting its increased efficiency, accuracy, and stability. This overview provides a summary of the fundamental aspects.

2. STAND ALONE SOLAR PV SYSTEM

Model of the Solar Power System

Utilizing a P-N junction semiconductor, the solar cell converts light energy into electrical energy, resembling a configuration comprising a single current source, a diode, and a combination of series and parallel resistances. The DC load receives the electricity produced by the photovoltaic conversion. The following mathematical formulas can be used to express the output current of a single solar cell. **[1]**

$$I_D = I_{so}\left(e^{ko(V+I.Rs)} - 1\right)$$

$$I = I_{ph} - I_D - I_p = I_{ph} - I_{so}\left(e^{ko(V+IRs)} - 1\right) - \frac{V + IR_S}{R_p}$$

Among them:

$$K_o = A_S / (B_s KT)$$

K:Bozeman constant $(1.38\times 10^{-23} J/K)$.

T:solar cell temperature(K).

As : The amount of charge of a single electron (1.6×10^{-19}).

Bs : Solar cell ideal P-N junction characteristic factor, between 1-5

Iso : Reverse saturation current

$$I_{so} = I_{sr}\left(\frac{T}{T_R}\right)^3 e^{k_o E_{gp}(1/T_r - 1/T)}$$

Where I_{sr} is the reverse saturation current at reference temperature Tr ; E_{gp} is the energy required to span the energy gap of a semiconductor material (the energy level of silicone is E_{gp} =1.11ev).

The relationship between the current source I_{ph} generated by a single solar cell and the illuminance intensity is:

$$I_{ph} = \left(I_{sc} + K_m(T - T_r)\right)\lambda / 100$$

where I_{sc} is the short circuit current at the reference temperature $T_r(K)$ and sunshine condition 100Mw/cm^2 ; Km is the solar panel short-circuit current temperature coefficient

(mA/ C); λ is the sunshine intensity (mW^2).

Consider the solar cell string parallel connection and ignore the I_p , get the × solar N_{sp} cell array board, as shown in Fig. 1. Considering the voltage and V_{pv} current I_{pv} of the solar array, the circuit characteristics of the solar array panel can be obtained below:

$$i_{pv} = N_p I_{ph} = N_p I_{so}\left(e^{kov_{pv}/N_s - 1}\right)$$

$$P_{pv} = i_{pv} \times V_{pv} = N_p I_{ph} V_{pv} - N_p I_{so} v_{pv}\left(e^{kov_{pv}/N_s} - 1\right)$$

Where P_{pv} is the solar output power V_{pv} is the output voltage of the solar array; is I_{pv} the output current of the solar array

Shading Effect Case

under uniform illumination, every solar panel can supply an identical current. However, if certain panels are shaded by objects such as clouds, the output current drops. Currently, the system predominantly relies on the output current during periods of minimal illumination. To mitigate the scenario where a low-illuminance solar cell is unable to provide current, a bypass diode is connected in parallel on both sides of the solar cell. Understanding the impact of partial shading involves assuming non-uniform solar illuminance. For instance, Fig. 3 depicts the fluctuation in solar illuminance, ranging from 100mW/cm^2 to 100mW/cm^2 and 50mW/cm^2, in panels affected by partial shading. Fig. 4 shows the P-V curves under a partial shading case and fixed ambient temperature. Prior to the alteration, the MPP was 900 W. Following the shift, there are two peaks: the MPP for the entire domain is 600 W, while the MPP for the local voltage zone is 400 W. The statistics reveal that shading on solar panels leads to the emergence of multiple peaks instead of a singular one. The level of peak production rises in correlation with the number of variations in solar illuminance intensity. Additionally, the conventional MPPT approach proves ineffective in determining the global Maximum Power Point (MPP) due to the transformation of the original peak into multiple peaks, leading to a decrease in the efficiency of solar energy conversion. Hence, there is a need for a new tracking rule to improve the efficiency of solar conversion.

3. MPPT TECHNIQUES

Perturbation and Observation (P&O) Technique:

The most commonly employed MPPT technique is Perturb and Observe (P&O). As indicated by its name, this method involves observing the optimization quantity P (Power) after perturbing the variable—either voltage or current. The controller adjusts the value of either V or I depending on the system's response. The algorithm of the Perturb and Observe (P&O) controller is depicted in Figure 8. In this process, the controller measures the values of V1 and I1 to determine the corresponding power, P1. Following this, the controller adjusts the reference voltage by changing the duty cycle of the dc-dc converter in a specific direction. Throughout this adjustment, the controller monitors and verifies the associated values of V2, I2, and P5. The direction of perturbation is correct if P2 is bigger than P1, otherwise Δd should be changed. $\frac{dp}{dv}$ is almost equivalent to zero at the greatest power point. In actuality, though, it is challenging to determine the point of V_{mpp}, and the operating point fluctuates close to MPP. Δd must be as little as feasible to minimise oscillation near MPP, but this lengthens the monitoring period. Thus, selecting the ideal duty cycle step size (d) is crucial. **[1]**

Incremental Conductance (INC) Technique:

An enhanced version of the P&O MPPT is the INC MPPT. It has superior control over P&O and lessens the impact of oscillation at MPP. It contrasts the conductance that is gradual (dp/dv) and instantaneous (I/V).

This is the dp/dv is given as:

$$\frac{dp}{dv} = \frac{d(VI)}{dV}\Big|I_{mpp}, V_{mpp} = 0$$

$$\frac{dp}{dv} = \frac{d(VI)}{dV} = I + V\frac{dI}{dV}$$

$$\frac{1}{V}\frac{dp}{dv}\Big|mpp = \frac{1}{V} + \frac{dI}{dV} = 0$$

Minor errors are acceptable in practical scenarios, and, in reality, $dp/dv = 0$ occur infrequently during practical implementation. The degree of permissible error (e) influences the sensitivity and oscillation at the operational point. Following Equation as a reference, the controller adjusts the duty cycle of the converter

$$\frac{dp}{dv} = \begin{cases} = e, I/V = -dI/dV, & \textit{no change} \\ > e, I/V > -dI/dV, & \textit{increase voltage} \\ < e, I/V < -dI/dV, & \textit{decrease voltage} \end{cases}$$

The INC algorithm is displayed. As efficient as P&O, the INC controller requires a more expensive controller.

The Fuzzy logic controller(FLC)

The fuzzy logic controller (FLC) makes decisions by using fuzzy logics. It then outputs the appropriate control signal. The FLC is primarily composed of three components, as illustrated in Fig. 8: fuzzification, rule-based inference engine, and defuzzification. As illustrated in Fig. 8, there is one output, Δd (k), and two inputs, error e(k) and change in error (K_{ce}) .Crisp inputs become fuzzy inputs through the fuzzification block. The application of rules and generation of fuzzy output are accomplished through the rule base. Subsequently, a defuzzification block is utilized to convert this fuzzy output into a precise, crisp output. Typically, the rule base is constructed using the Mamdani block, and the output from the Fuzzy Logic Controller (FLC) is derived using the center of gravity.

According to, for P&O based FLC, e(k) = dP/dV and ce(k) = e(k) - e(k-1). To determine the position and direction of DC-DC converter operation, utilise the e(k) and ce(k). The left side of the MPP is the point of action if e(k) is positive; otherwise, the right side of the MPP is where it is. Likewise, a positive or negative value of ce(k) indicates the tracking direction in detail. In Figure 12, the membership functions (MF) for both input and output are depicted. The selection of the appropriate rule and the range of membership functions (MFs) is a critical aspect of implementing the Fuzzy Logic Controller (FLC) system. Therefore, possessing ample practical experience is just as essential as having a sound technical understanding of the model.

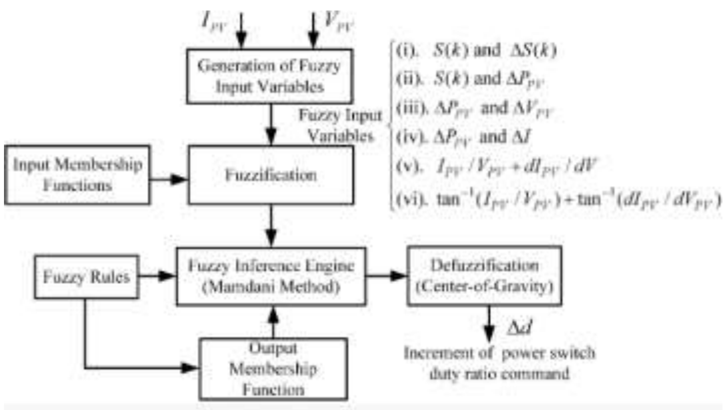

Fig.1. Fuzzy logic controller algorithm for MPPT technique

Artificial Neural Network (ANN) Technique

Artificial Neural Networks (ANNs) consist of numerous artificial neurons connected to weights, mimicking human behavior. The unique feature of ANNs is their ability to address intricate mathematical problems without explicitly computing the complex underlying structures.The typical architecture of an artificial neural network (ANN) involves three layers: input, output, and a hidden layer, as illustrated in Figure . In the context of solar PV Maximum Power Point Tracking (MPPT), the input to the ANN encompasses system parameters such as temperature, irradiance, PV current, and voltage, either individually or in various combinations. The output may manifest as a duty cycle signal or the desired voltage value.

Similar to the human brain, an artificial neural network (ANN) requires training to recognize patterns in different combinations of input and output. The backpropagation algorithm is commonly employed for this training process. The adjustment of weights in the hidden layers involves using the weight error ε(w), which represents the disparity between the model's estimated output and the actual measured output. Through effective training and weight adjustments, the ANN controller becomes capable of reliably identifying the Maximum Power Point (MPP) at different temperatures and levels of irradiance. **[10]**

Adaptive P&O or INC Technique

The dynamic and steady-state responses of the controller in Perturb and Observe (P&O) or Incremental Conductance (INC) control approaches are determined by the duty cycle's step size. A higher step size facilitates a quicker dynamic response, albeit with an accompanying increase in steady-state losses. Similarly, a reduced step size alters the balance in the opposite direction. For an improvement in both dynamic and steady-state responses concurrently, adaptive Incremental Conductance (INC) or Perturb and Observe (P&O) is employed, incorporating a variable step size. The step size is adjusted using this approach, and its value falls within $\Delta d_{min} < \Delta d < \Delta d_{max}$**.** Based on a series of rules, such as the slope of dp/dv, the step size of the duty cycle is continually reduced as the operating point moves towards MPP. A fuzzy control MPPT with adaptive P&O is proposed. **[10]**

Hybrid MPPT Technique

Every MPPT technique has its own strengths and weaknesses. The hybrid MPPT technique leverages features from two or more MPPT methods to enhance overall performance and reduce errors. Zhang et al. (2013) propose the hybrid adaptive Perturb and Observe (P&O) MPPT. The Adaptive Perturb and Observe (P&O) MPPT technique precisely determines the maximum power point, while the Fixed Voltage Fraction MPPT technique estimates the MPP. Combining these two MPPT methods is reported to result in reduced operation time and decreased steady-state errors. Likewise, multiple hybrid combinations, such as ANN-fuzzy control, P&O-ANN, current friction-P&O, and ANN-fuzzy control, have been proposed in literature, showcasing their ability to track the Maximum Power Point (MPP) independently of the device and environmental changes.

Voltage Fraction Technique

V_{oc} *and* V_{mpp} have a linear connection at various temperatures and irradiances. With this method, an easy-to-create and reasonably priced MPPT can be created. $V_{mpp} = K_{oc} V_{oc}$ current of short circuit.

The main disadvantage of this method is its inconsistent output and fluctuating voltage. To measure Vo, this technique involves briefly opening the load circuit.

Lookup Table Based MPPT Technique

According to this control method, the Memory-based system retains Maximum Power Points (MPPs) through thorough training under varying environmental conditions. The approximate optimal operating point is determined in the process through a lookup table. portrays the design of MPPT based on a lookup table.

Current / Voltage Feedback Technique

To ensure a stable output voltage and maximize power extraction, this method utilizes a basic DC-DC converter. An error signal is generated by comparing the reference current with the module's output current. The feedback mechanism relies on a PID controller, which uses the error signal to generate the correct duty cycle. Properly tuning the PID is essential for improved performance.

MPPT Schemes for Partial Shading Conditions

Based on fundamental ideas like $dP = dV = 0 \text{ and } P_{mpp} = f(V)$, the traditional MPPT controller is made to track MPP. The efficiency of a traditional controller is indirectly hampered in partial shading situations because it is unable to distinguish between the local maximum power point (LMPP) and the global maximum power point (GMPP). Therefore, it must alter the traditional MPPT's design arrangement. The various methods for GMPP tracking are discussed in detail and are explained next. **[8]**

Power Curve Slope Detection Technique

A modified version of the continuous search scheme is the Power Slope technique. Using this procedure, the dP/dV sign is verified at several operation points and it is for evaluating the Local MPP. MPP is monitored using the basic P&O approach and to find GMPP, a power slopes subroutine is employed.in half shaded areas. V curve also shows that if the power available at two LMPP is less than the power at existing MPP, than existing MPP is a Global MPP. The maximum power point is updated if the LMPP exceeds the preceding one; if not, the controller changes the direction of the current search and begins a new one. This feature shortens the tracking duration. With a low-cost microcontroller, the power curve approach is straightforward to apply. Patel and Agarwal (2008) have verified and put the hardware model into practice. To improve the controller's performance and dependability, the duty step size (ΔV) and timer selection must be done correctly. **[6]**

Table 1

Comparison of Different MPPT Techniques for Partial Shading Condition

MPPT Technique	Analog or Digital	Sensed Parameter	cost	Complexity	Convergence Speed	PV Array Dependent	Parameter Tuning	Application
Simple power curve scanning	Digital	V, I	low	simple	slow	No		Two sided roof pv system
Power curve slope detection	Digital	V, I	Medium	Medium	Medium	No	No	-
Load Line Matching	Digital	V, I	Medium	Medium	Medium	No	No	-
Fibonacci Search	Digital	V, I	high	complex	Medium	Yes	Yes	For simple application Experimental
PSO	Digital	V, I	high	complex	Fast	Yes	Yes	Study hybrid vehicle
DMPPT	Both	V, I	high	Medium	Fast	No	No	high efficiency system
Fixed Structure Reconfiguration	Both	V, I	high	simple	-	Yes	No	For analysis and study

Table 2

Comparison of Different MPPT Techniques for Normal Irradiance

MPPT Technique	Parameter Tuning	Sensed Parameters	PV Array Dependent	Analog or Digital	Cost	Complexity	Merit	Demerit
Curve Fitting	Yes	V or I	Yes	Digital	INEX	Simple	Use simple logic	Continuous power loss
Current Fraction	Yes	I	Yes	Analog	INEX	Simple	No computation hardware required	Power loss during change in weather
Voltage Fraction	Yes	V	Yes	Analog	INEX	Simple	No computation hardware required	Power loss during change in weather
Lookup Table	Yes	V,I or G,T	Yes	Digital	INEX	Simple	Simple logic	Periodic tuning required
Current / Voltage Feedback	No	V or I	Yes	Both	INEX	Simple	Easy to implement	Power loss due to change in weather
P&O	No	V,I	No	Both	EX	Medium	Good tracking capability	Continuous oscillation and tracking speed
INC	No	V,I	No	Digital	EX	Complex	Low oscillation near MPP	Complexity in implementation
FLC	Yes	V,I or G,T	Yes	Digital	EX	Complex	Good response and little oscillation near MPP	Complexity in implementation and selection of proper range of operation
ANN	Yes	V,I,G	Yes	Digital	EX	Complex	Good response and less oscillation near MPP	Parameter tuning
Adaptive P&O	Yes	V,I	Yes	Digital	EX	Medium/ Complex	Fast convergence speed	Advanced microcontroller is required for implementation
Hybrid MPPT	Yes	V,I	Can't say	Digital	EX	Medium/ Complex	Fast convergence speed	Higher cost of implementation

4 Conclusion

This paper addresses and explores key methodologies for Maximum Power Point Tracking (MPPT) in solar systems. The content serves as instructional material for understanding solar MPPT techniques. The paper makes an effort to provide a detailed description of important techniques related to Global Maximum Power Point Tracking (GMPPT). Additionally, it contributes a comprehensive comparative analysis, considering factors such as performance, cost, circuit complexity, and other relevant parameters associated with MPPT. The findings from this analysis can guide the selection of an appropriate MPPT method. The paper includes illustrative simulation exercises showcasing the power generation performance achieved by various MPPT controllers.

Moreover, it enhances understanding by presenting numerical comparisons. The review work also delivers a succinct analysis and comparison of MPPT techniques, particularly in the context of partial shading conditions. This paper is likely to be beneficial for solar PV system manufacturers and designers of solar inverters.

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