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Maximum power point tracking techniques for low-cost solar photovoltaic applications – Part II: Mathematical Calculation and Measurement and Comparison, criteria on choices and suitable MPPT techniques

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Abstract: In the last decade, there has been a substantial surge in the advancement of research into the maximum power point tracking (MPPT) controller. The MPPT approaches, on the other hand, continue to be in high demand due to the ease and simplicity with which tracking techniques can be implemented on the maximum power point (MPP). Diverse MPPT approaches and their modifications from various literature are categorized and thoroughly explored in this work, which is divided into two sections. The discussions are centered on the primary goal of attaining the most extraordinary feasible MPPT technique that produces the best results at the lowest possible expense. In order to determine which MPPT approaches to use, evaluations from earlier literature are used to guide the decision. In this section, we will examine the evaluation of the MPPT technique in two sections. Previously, in Part I, we explored the MPPT techniques based on constant parameters and trial-and- error. Part II of this article will examine the MPPT technique, which is based on mathematical computation, measurement, and comparison, and the algorithm development that has occurred in recent years. Furthermore, this section's assessment for selecting MPPT approaches is based on previous literature reviews. To aid with this selection, the following criteria for the MPPT approach are proposed: sensors and analog/digital requirements, cost-effectiveness, simplicity, stability, efficiency, and tracking speed. This enables the reader to select the MPPT technique that is most appropriate for their application.

Key words: Incremental Conductance, maximum power point tracking, Measurement and Comparison, Perturb and Observe, solar photovoltaic, trial-and-error

1. Introduction

Solar energy (PV) is the most promising renewable energy source. It is even considered one of the best green energy alternatives to traditional energy sources [1–4]. This energy source is abundant and non-toxic. With no waste, no greenhouse gases (CO_2, NO_x, or SO_2), no poisonous gases (SO_2 and particles), no greenhouse gases (SO_2 and particulates), solar energy production benefits the environment [5–8]. As a result, scientists developed a photovoltaic (PV) renewable energy idea. This market grew by around 30% each year earlier in the decade [9]. Low maintenance and long life are also cost advantages. Massive PV power generation systems can also aid home, health, education, and agriculture economies [10].

External influences like temperature and irradiation affect non-linear PV systems. The PV's maximum power point (MPP) fluctuates with the conditions. MPP tracking is a decade-old technique (MPPT). Due to PV systems' low energy conversion, an MPPT system that can efficiently track the MPP is required to maximize power extraction and make them more reliable and efficient [11–13]. MPPT is also regarded as the most cost-effective option for updating the total PV system [14, 15].

Many MPPT algorithms are still in demand and being researched due to their convenience and simplicity. One article reviewed and categorized MPPT techniques. Subudhi and Pradhan [13], Verma *et al*. [16], Esram and Chapman [17], Ali *et al*. [18], Kamarzaman and Tan [19], Bendip *et al*. [20], Gupta *et al*. [21], and Podder *et al*. [22] examine and classify MPPT techniques. The articles compare the way of generating variables. The benefits and cons of each technique have been examined by Tajuddin *et al*. [23], Danandeh and Mousavi [24], Bollipo *et al*. [25], Karami *et al*. [26], and Mao *et al*. [27]. Motahhir *et al*. [28] categorized MPPT based on embedded target analog/digital requirements and cost. Poor MPPT selection criteria plague most investigations. This research gives a simple explanation that considers sensor, analog/digital requirements, and cost. Several conventional MPPT techniques were previously reviewed in Part I, namely "Maximum power point tracking techniques for low-cost solar photovoltaic applications – Part I: constant parameters, and trial-and-error" [29].

2. MPPT techniques

The main goal of implementing MPPT is to ensure maximum power extraction from the PV module in any weather. Constant parameters, trial-and-error, mathematical calculation, as well as Measurement and Comparison are the four MPPT approaches. The first two strategies were described in Part I, and the latter two will be discussed here.

2.1. Based on Mathematical Calculation

Mathematical computations are used in this procedure. Table 1 summarizes the basic description and associated works of MPPT techniques based on Mathematical Calculation, with the specifics provided below.

Table 1. Basic description and related works to MPPT technique based on Mathematical Calculation

MPPT technique	Description of MPPT technique	Related works
Incremental Conductance (IncCond)	– IncCond method provides excellent tracking in rapidly changing atmospheric conditions. The efficiency of the IncCond method is approximately the same as that of the P&O method [33, 34]. – Advantages: Good performance under conditions of a fast-changing atmosphere, lower oscillations than even the P&O optimize method. – Disadvantages: Complex, fixed step size has low convergence losses, oscillations around the MPP, and cannot cope with rapidly changing atmospheric conditions.	– References [37–40] propose modifying the step-size variable to solve the IncCond method problem with a fixed step size. – Mei *et al.* [41] offers an advanced variable step-size approach to improve dynamic tracking and tracking accuracy. The difference in this method is that the step-size mode can be switched by the threshold function point (C) of the PV output power exponential (P^n) and the absolute value of the PV power derivative ($\lvert \mathrm{d}P/\mathrm{d}I \rvert$). – Zakzouk *et al.* [42] presented a variable step size based on PV power change. The proposed solution simplifies the structure and reduces processing time by solely relying on changes in PV power. The approach also saves money due to its simplified construction.
Differentiation method	– Based on the property in which the MPP resides by solving equations that perform various calculations. – Advantage: Good accuracy. – Disadvantage: Expensive to implement because it is a powerful processor is required.	– Xiao *et al.* [43] proposed centered differentiation, which increases accuracy in finding MPP and reduces oscillations around MPP.
Current Sweep method	– Based on the panel output power derivative of the panel current. The current panel is a decaying exponential sweep. – Advantages: Fast-tracking and inexpensive because it is only current based. – Disadvantage: Only if the tracer unit's power usage is less than the increase in power carried by the total PV system.	– Tsang and Chan [44] apply the Current Sweep method under partial shading conditions.

Continued on next page

Table 1 – *Continued from previous page*

MPPT technique	Description of MPPT technique	Related works
Feedback of power variation with voltage or current	– Works with computing the slope dP_{PV}/dV_{PV} for feedback power variation with voltage and dP_{PV}/dI_{PV} for feedback power variation with the current. – Advantages: Fast and accurate in tracking MPP. – Disadvantage: Complex computing, only suitable for stable atmospheric conditions.	– Park and Song [45] implemented the dP/dV method with an inverse-SEPIC converter (II-SEPIC).
Parasitic Capacitance	– Modeled as a capacitor connected in parallel to each cell in a PV module. The total Parasitic Capacitance increases with the parallel connection of the modules. – Advantage: The method's efficiency is increased in high-power PV systems with multiple module coverage and connected in parallel. – Disadvantage: cannot be avoided because it is used as a parameter in finding the MPP.	– Wu *et al.* [46] applied the Parasitic Capacitance method to the PV model by ideally combining a PV diode with a constant voltage source representing the threshold voltage instead of an intrinsic PV diode with the Shockley diode equation.
β method	– Tracks the maximum power using the approximation, whereas other conventional methods track the exact MPP. – Advantages: Fast and accurate tracking. – Disadvantage: Little effect on sudden increase or decrease in irradiation level.	– Wen *et al.* [47] developed this method for the need to predict the global MPP location with increasing accuracy and zero oscillation at a steady state.
I_{MPP} and V_{MPP} computation	– Using calculations from equations involving irradiation rate and temperature. The PV module is forced to operate on MPP after I_{MPP} and V_{MPP} are obtained by feedback control. – Advantage: Fast-tracking MPP. – Disadvantage: Equations involving temperature and degree of irradiation are not easy to measure.	– Abe *et al.* [48] proposed a simple method for estimating the solar irradiation, G, from I_{MPP} and the PV temperature, T, based on V_{MPP}.
Ripple Correlation Control	– Profit from the ripple created by switching converters to the PV array. It is possible to find MPP without delay by measuring circuit parameters at two switching ripple points. – Advantages: Simple, inexpensive, does not require information on the characteristics of the PV array, no need to add perturbation. – Disadvantages: Designing the compensator. Along with the PV panel, it exhibits highly non-linear dynamics.	– Kimball and Krein [49] developed this method digitally. The same authors also developed the discrete-time RCC (DRCC) [50]. The RCC method can work on a stable digital implementation. – Other studies modifying this hysteresis-based method were carried out by Lim and Hamill [51, 52].

2.1.1. Incremental Conductance (IncCond)

The I-V characteristic slope is used to track the MPP in the PV system [30–32]. The IncCond approach tracks well in rapidly changing weather. The IncCond method is nearly as efficient as the P&O method [33, 34]. The simple method of IncCond is fixed step size with direct control as done by [35]. Figure 1 depicts the IncCond method's flowchart.

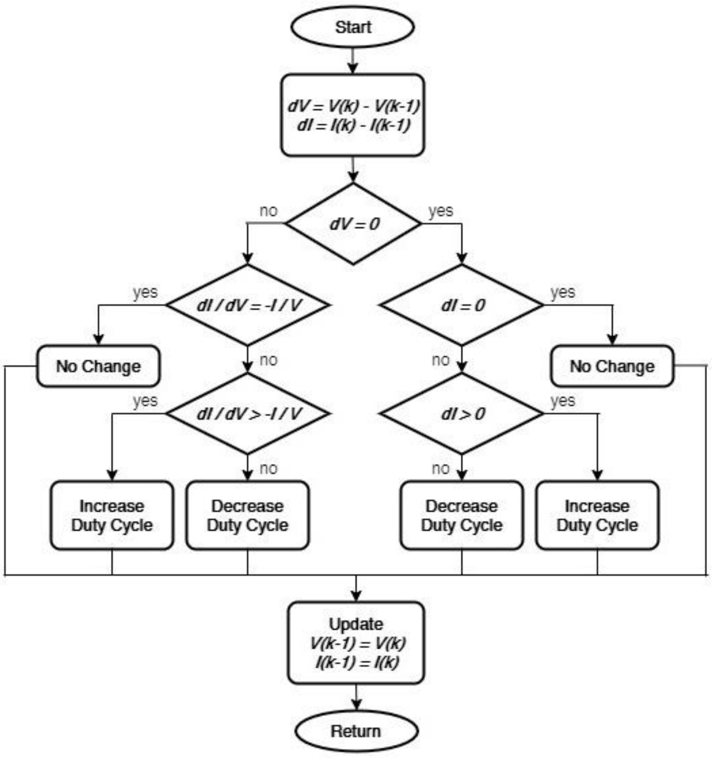

Fig. 1. IncCond method

The IncCond method makes use of differentiating power against PV voltage. The MPP lies when the differentiation is zero [36]. The basic equation for the IncCond method is given by:

$$\frac{\mathrm{d}I}{\mathrm{d}V} = -\frac{I}{V}, \quad \text{at MPP,} \tag{1}$$

$$\frac{\mathrm{d}I}{\mathrm{d}V} > -\frac{I}{V}, \quad \text{left of MPP,} \tag{2}$$

$$\frac{\mathrm{d}I}{\mathrm{d}V} < -\frac{I}{V}, \quad \text{right of MPP.} \tag{3}$$

The left side of the equation is IncCond, and the right is instantaneous conductance. The PV module is at the MPP when the ratio of change in output conductance is negative. The PV module is at the MPP when the output conductance change ratio is negative. This method tracks the true MPP irrespective of PV characteristics.

The step-size IncCond approach relies on the change in PV power due to voltage variation. When irradiation changes rapidly, this causes steady-state oscillations around the MPP, resulting in decreased performance. A fixed step-size IncCond technique exhibits low convergence losses and oscillations around the MPP. This standard IncCond method's flaws are addressed in particular literature. The IncCond approach with a fixed step size is addressed in the references [37–40]. Figure 2 depicts the variable step-size flowchart.

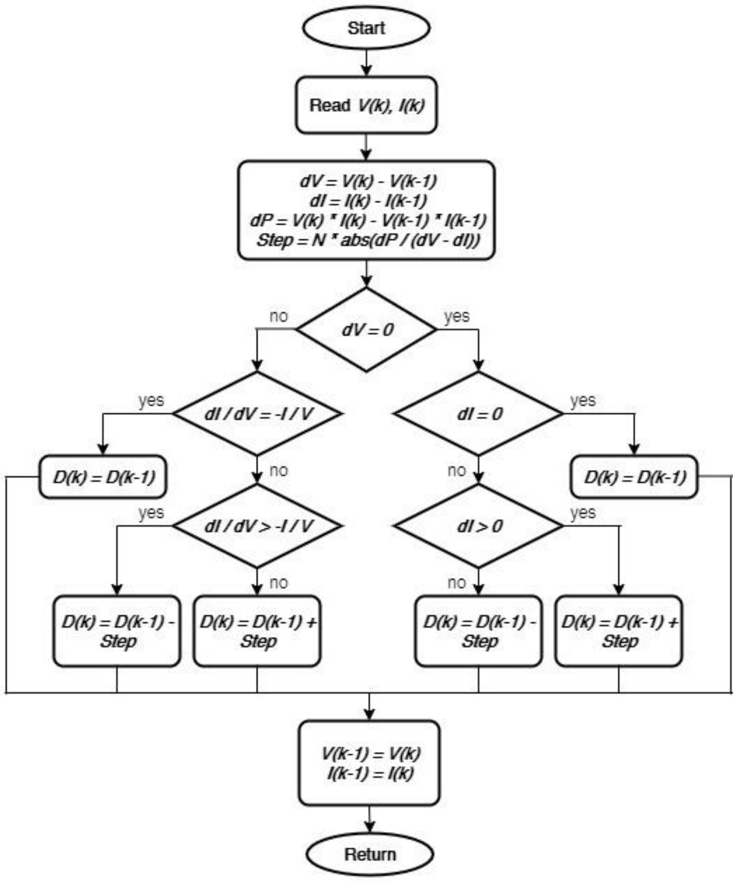

Fig. 2. IncCond step-size variable flowchart

The equation of the proposed method is shown in (4).

$$D(k) = D(k-1) \pm N \times \left| \frac{\mathrm{d}P}{\mathrm{d}V - \mathrm{d}I} \right|, \tag{4}$$

where $D(k)$ and $D(k-1)$ are the converter duty cycle at the instant (k) and the previous duty cycle $(k-1)$. While N is the adjusted scale factor in the sampling period to determine the step size.

Literature [41] proposes an advanced variable step-size method to simplify tracking dynamic and tracking accuracy to become more effective. The difference in this method is that the step-size mode can be switched by the threshold function point (C) of the PV output power exponential (P^n) and the absolute value of the PV power derivative ($|\mathrm{d}P/\mathrm{d}I|$) as

$$C = P^n \times \left|\frac{\mathrm{d}P}{\mathrm{d}I}\right|, \tag{5}$$

where n is the index. The product of the first-degree exponential ($n - 1$) PV power and its derivatives are applied to control the step size. The flowchart of the proposed method is shown in Fig. 3.

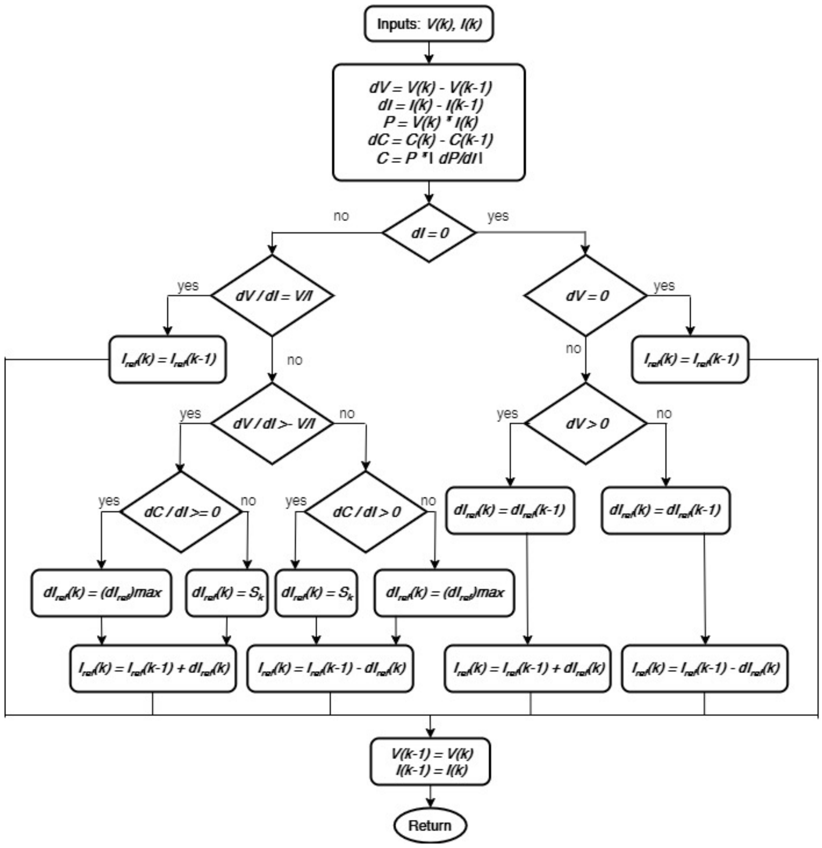

Fig. 3. Flowcharts are proposed by literature [41]

Literature [42] proposed a variable step size based on PV power change. The proposed solution simplifies the structure and reduces processing time by modifying the PV power. The approach also saves money due to its simplified construction. Figure 4 is a proposed schematic flowchart. A change in the converter duty cycle is represented by changing the step size. Equations provide the following:

$$dD = N_2|dP|, \tag{6}$$

where N_2 is the preset scale factor.

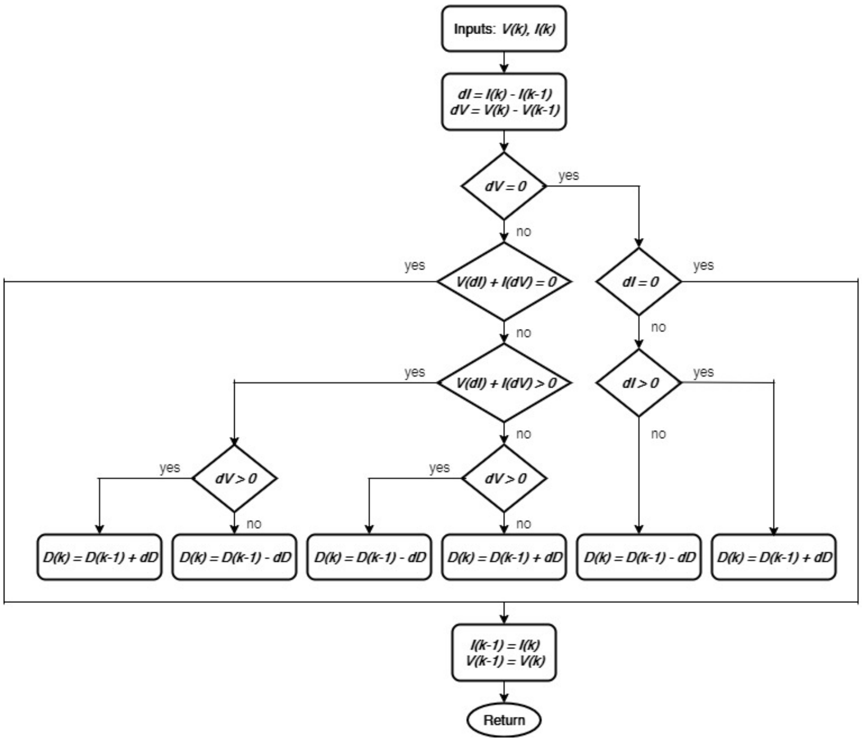

Fig. 4. Flowchart of the IncCond method by literature [42]

2.1.2. Differentiation method

The MPP of the PV system from the differentiation method [53, 54] is determined by solving the following:

$$\frac{dP}{dt} = \frac{d(IV)}{dt} = I\frac{dV}{dt} + V\frac{dI}{dt} = 0. \tag{7}$$

To implement this method, a powerful processor is required because there are at least eight calculations that must be done quickly, including measuring I and V, calculating dV and dI measurements for the dt time range, calculating $I + dV/dt$, $V + dI/dt$ and $I \times \frac{dV}{dt} + V \times \frac{dI}{dt}$. This made implementing the differentiation method expensive.

Instead of Euler's numerical differentiation method, literature [43] proposes centered differentiation. Centered differentiation is expressed in (8) and (9). Three-point measurement to approach the derivative value at the center point (v_k, p_k) is $(v_k - 1, p_k - 1)$; (v_k, p_k); and $(v_k + 1, p_k + 1)$. The local truncation error for centered differentiation, as shown in (8), is equal to $0(\Delta V^3)$ indicating second-order accuracy. Therefore, this method produces better accuracy than Euler's method for numerical differentiation. The centered differentiation flowchart is shown in Fig. 5. In this algorithm, "Sched" is a variable used for scheduling the computation load of MPPT. While the K_ε parameter is used to determine how big the step takes in the gradient direction.

$$\frac{\mathrm{d}P}{\mathrm{d}v} = f(v, p), \tag{8}$$

$$f(v_k, p_k) = \frac{p_k + 1 - p_k - 1}{2\Delta V} + 0(\Delta V^3). \tag{9}$$

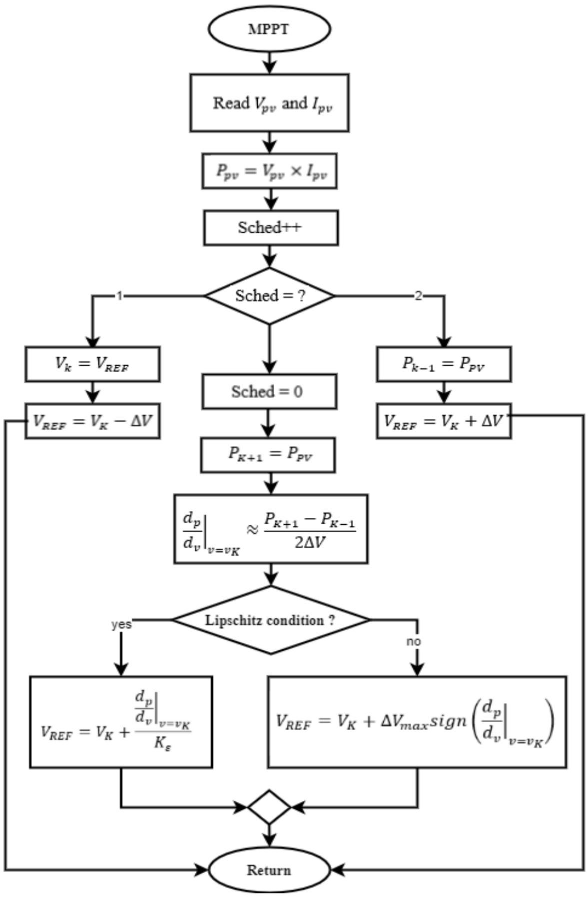

Fig. 5. Flowchart centered differentiation method

2.1.3. Current Sweep method

To compute the MPP voltage from the characteristic curve, the Current Sweep method [44, 55, 56] uses a swept waveform for PV currents. The Current Sweep waveform function's derivative is directly proportional to

$$i(t) = k_1 \frac{\mathrm{d}i}{\mathrm{d}t}. \tag{10}$$

Then the solution is

$$i(t) = k_2 e^{t/k_1}. \tag{11}$$

Here, k_2 is taken as I_{MPP} in the MPP. Again, at the MPP

$$\frac{\mathrm{d}p(t)}{\mathrm{d}t} = \frac{\mathrm{d}\left(v(t)i(t)\right)}{\mathrm{d}t} = i(t)\frac{\mathrm{d}v(t)}{\mathrm{d}t} + v(t)\frac{\mathrm{d}i(t)}{\mathrm{d}t} = 0. \tag{12}$$

Using (10) in (12) we get:

$$\frac{\mathrm{d}p(t)}{\mathrm{d}t} = \left(k_1\frac{\mathrm{d}v(t)}{\mathrm{d}t} + v(t)\right)\frac{\mathrm{d}i(t)}{\mathrm{d}t} = 0, \tag{13}$$

where $i(t)$ is the result of (11), followed by V_{MPP} using (13). The reference point updates at predetermined intervals. So, provided the proportionality coefficients k_1 and k_2 are chosen appropriately, this technique produces accurate results. This method works best when the tracer unit's power consumption is less than the overall PV system's power increase.

2.1.4. Feedback of power variation with voltage or current

This method [57–59] works with computing the slope $\mathrm{d}P_{\mathrm{PV}}/\mathrm{d}V_{\mathrm{PV}}$ for feedback power variation with voltage, and $\mathrm{d}P_{\mathrm{PV}}/\mathrm{d}I_{\mathrm{PV}}$ for feedback power variation with the current. Figure 6 shows the feedback of the power variation method. To maximize power control, set the derivative $\mathrm{d}p/\mathrm{d}v$ or $\mathrm{d}p/\mathrm{d}i$ to zero. This technology measures and maximizes power at the load terminals. This method necessitates a high-performance converter.

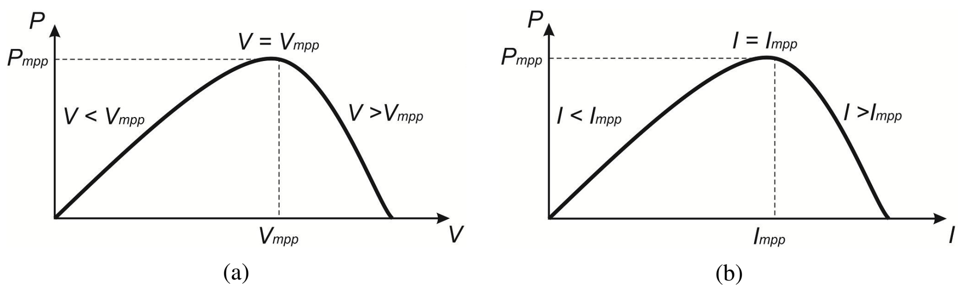

Fig. 6. Curve on the feedback of power variation method: (a) with voltage; (b) with the current

2.1.5. Parasitic Capacitance

The effect of the PV cell parasitic junction capacitance, C_p, is added to the IncCond technique. When the PV panel works outside the MPP, the Parasitic Capacitance approach method [17, 46, 60–62] causes the system dynamics to slow down. This disadvantage cannot be prevented because it is an MPP parameter. Parasitic Capacitance is described as a parallel capacitor connected to each PV cell. Thus, the overall Parasitic Capacitance grows with parallel module connection. A high-power PV system with multiple module coverage and connected in parallel is recommended for maximum efficiency. The capacitance effect is known by adding the current through the capacitance as $i\,(t) = C_p \mathrm{d}V/\mathrm{d}t$ in the PV panel model equation as

$$I = I_{\mathrm{PV}} - I_o \left[\exp\left(\frac{V + IR_s}{aV_t}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} + C_p \frac{\mathrm{d}v}{\mathrm{d}t}\,. \tag{14}$$

It can be rewritten as

$$I = f\,(v) + C_p \frac{\mathrm{d}v}{\mathrm{d}t}\,, \tag{15}$$

where

$$f\,(v) = I_{\mathrm{PV}} - I_o \left[\exp\left(\frac{V + IR_s}{aV_t}\right) - 1\right] - \frac{V + IR_s}{R_{sh}}\,. \tag{16}$$

The power output from the PV is represented as

$$P = V\left(f\,(v) + C_p \frac{\mathrm{d}v}{\mathrm{d}t}\right). \tag{17}$$

The MPP is located at the point where $\frac{\mathrm{d}P}{\mathrm{d}V} = 0$, so that

$$g_p = \frac{\mathrm{d}f\,(v)}{\mathrm{d}v} + C_p\left(\frac{\dot{V}}{V} + \frac{\ddot{V}}{\dot{V}}\right) + \frac{f\,(v)}{\mathrm{d}V} = 0, \tag{18}$$

where $\frac{\mathrm{d}f\,(v)}{\mathrm{d}v}$ is the instantaneous conductance, $C_p\left(\frac{\dot{V}}{V} + \frac{\ddot{V}}{\dot{V}}\right)$ is the incremental inductance, and $\frac{f\,(v)}{\mathrm{d}V}$ is the inducted ripple of parasitic conductance. The converter's AC ripple component is determined as the first and second derivatives of the array voltage. The conductance of an array is determined as follows:

$$g_p = \frac{P_{gp}}{V_o^2}\,, \tag{19}$$

where P_{gp} is the average ripple power and V_o is the voltage ripple.

The current and voltage of the PV array are measured as inputs to the circuit. The high-pass filter removes the dc component from V. The two multipliers produce ac V_o^2 and P_{gp} signals. Then filtered with a low-pass filter and leave the dc components V_o^2 and P_{gp}.

2.1.6. β method

This method [63] tracks the maximum power using the approximation, whereas other conventional methods track the exact MPP. Literature [47] developed this method for the benefit of predicting global MPP locations by increasing the accuracy and zero oscillation at a steady state. The main advantage of the β method is that it can perform the fast-tracking of data. Analysis of the I-V characteristics of the PV module leads to an intermediate variable, β, which is formulated as

$$\beta = \ln\left(\frac{I_{\mathrm{PV}}}{V_{\mathrm{PV}}}\right) - cV_{\mathrm{PV}} = \ln\,(I_s c)\,, \tag{20}$$

where I_s is the reverse saturation current and c is the diode constant given as $c = q/(AkTN_s)$ where q is the electronic charge, A is the ideal factor, k is the Boltzmann constant, T is the temperature in Kelvin and N_s is the number of cells connected in series. It appears that β depends only on temperature and not on irradiation.

The value of the β MPP is in a small range and remains constant when the temperature varies within a fixed range. This quantity can be represented as β min for the lower limit to β max for the upper limit. The lower limit in the MPP refers to irradiation and the upper limit to the maximum temperature. The flowchart β method is shown in Fig. 7. During the first stage of the algorithm, βg, to calculate the duty-cycle correction, M, the β value corresponding to the temperature of the PV module is used. Whereas βa shows the actual value of β at a certain moment. The β approach is frequently paired with other methods. Large iterative steps can easily approach the MPP. Other techniques then work to get the MPP.

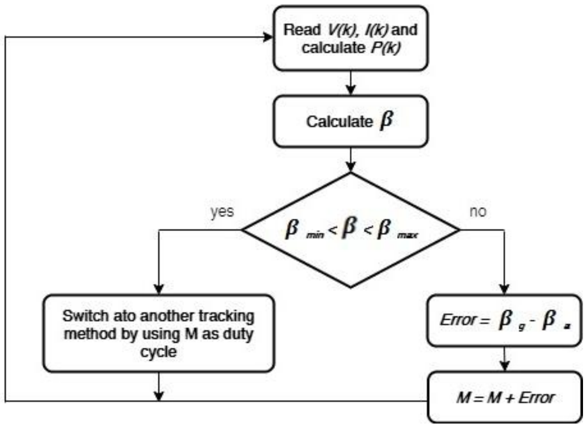

Fig. 7. Flowchart β method

2.1.7. I_{MPP} and V_{MPP} computation

The I_{MPP} and V_{MPP} computation [64] methods use calculations from equations involving irradiation rate and temperature. Feedback control is used to force the PV module to operate on the MPP after I_{MPP} and V_{MPP} have been obtained. The PV voltage, V_{PV}, and the PV current, I_{PV} above are calculated as

$$I_{\text{PV}} = \left[I_s + I_{SC} \left(\frac{G}{G_{\text{ref}}} - 1 \right) + \mu \left(T - T_{\text{ref}} \right) \right] N_p \,, \tag{21}$$

$$V_{\text{PV}} = \left[V_s + \beta \left(T - T_{\text{ref}} \right) - R_s \left(\frac{1}{N_P} - I_S \right) - \frac{k I_{\text{PV}}}{N_p} \left(T - T_{\text{ref}} \right) \right] N_S \,, \tag{22}$$

where V_s and I_s are the terminal voltages and output currents of the PV module, respectively. G and T are solar irradiation and temperature, respectively. G_{ref} and T_{ref} are the standard solar irradiation and standard temperatures, respectively. Then I_{SC} is the short circuit current in Standard Temperature Condition (STC), while μ is the temperature coefficient in I_{SC}. β is the module open circuit voltage temperature coefficient, R_s is the module series resistance and k is the curve correction factor. Whereas N_S and N_p are the numbers of modules connected in series and parallel, respectively. Furthermore, the output power of the PV module is

$$P_{\mathrm{PV}} = V_{\mathrm{PV}} I_{\mathrm{PV}} = I_{\mathrm{PV}} \left[V_s + \beta (T - T_{\mathrm{ref}}) + R_s I_S - \frac{I_{\mathrm{PV}}}{N_p} \left[R_s + k (T - T_{\mathrm{ref}}) \right] \right] N_S . \tag{23}$$

Then I_{MPP} and V_{MPP} are

$$I_{\mathrm{MPP}} = \frac{N_P}{2} \frac{V_S + \beta (T - T_{\mathrm{ref}}) + R_s I_S}{R_s + k (T - T_{\mathrm{ref}})} , \tag{24}$$

$$V_{\mathrm{MPP}} = \frac{N_P}{2} V_S + \beta (T - T_{\mathrm{ref}}) + R_s I_S . \tag{25}$$

However, determining G and T is a complex matter. Literature [48] proposes an approach to estimate G from I_{MPP} and T from V_{MPP}. Equations (26) and (27) are the final form of the proposed calculation.

$$T = \left(\frac{P_{\mathrm{MPP}} G_{\mathrm{STC}}}{G I_{\mathrm{MPP,STC}} (V_{\mathrm{MPP}}(G))} - 1 \right) \frac{1}{\tau\gamma} + T_{\mathrm{STC}} , \tag{26}$$

$$G \approx 1000 \frac{\mathrm{MPP}}{I_{\mathrm{MPP,STC}}} , \tag{27}$$

where STC (standard test conditions) are $G = 1\,000$ W/m^2 and $T = 25°$C, γ and τ are the thermal coefficient of power and the correction factor of γ, respectively.

2.1.8. Ripple Correlation Control

The Ripple Correlation Control (RCC) approach [65, 66] uses the ripples that occur when switching converters are given to a PV array. The technique can discover the most significant power point without averaging the switching ripple by measuring the circuit parameters at two places. Since ripple occurs in the switching converter, no perturbation is needed. With the help of Eq. (28) and (29) the PV system's voltage and current can be compared to the MPP. RCC reduces ripple and drags PV voltage and current to the MPP.

$$\frac{\mathrm{d}v}{\mathrm{d}t} > 0 \quad \text{or} \quad \frac{\mathrm{d}i}{\mathrm{d}t} > 0 \quad \text{and} \quad \frac{\mathrm{d}p}{\mathrm{d}t} > 0 \rightarrow V < V_{\mathrm{MPP}} \quad \text{or} \quad I < I_{\mathrm{MPP}} , \tag{28}$$

$$\frac{\mathrm{d}v}{\mathrm{d}t} > 0 \quad \text{or} \quad \frac{\mathrm{d}i}{\mathrm{d}t} > 0 \quad \text{and} \quad \frac{\mathrm{d}p}{\mathrm{d}t} < 0 \rightarrow V > V_{\mathrm{MPP}} \quad \text{or} \quad I < I_{\mathrm{MPP}} . \tag{29}$$

The early development of this method was analog. Literature [49] developed this method on a digital basis. The same author also developed discrete-time RCC (DRCC) [50]. The RCC method can work on digital implementations stably. Other studies modifying this hysteresis-based method were carried out by references [51, 52].

2.2. Based on Measurement and Comparison

The method compares the magnitude of an external parameter to a known MPP. Table 2 outlines MPPT strategies based on Measurement and Comparison, with details provided below.

Table 2. Basic description and related works to MPPT technique based on Measurement and Comparison

MPPT technique	Description of MPPT technique	Related works
Look-up Table	– Work with the comparison of previously stored values. V_{PV} or I_{PV}, to the V_{MPP} or I_{MPP} are tracked by comparing the PV panel output with previously stored data. – Advantages: Simple and fast-tracking. – Disadvantage: Requires a large amount of storage.	– Jin *et al.* [72] proposed the UI-RI hybrid Look-up Table method as an alternative to the conventional single UI Look-up Table method.
Load Voltage/ Load Current Maximization	– Types of load often used are resistive, voltage-source, current-source, or a combination of these types. – Advantage: Only requires one sensor. – Disadvantage: Did not achieve the exact MPP, because this method is based on the assumption that the power converter is lossless.	– Kumar *et al.* [77] proposed a voltage-based load method using an adaptive step size. Adaptive step size is varied according to the slope of versus duty ratio characteristic.

2.2.1. Look-up Table

This technique [67–72] compares previously stored values. Figure 8 depicts the Look-up Table method. This stored value represents a collection of conceivable environmental circumstances. This table can be generated using climatic data or manufacturer standards. The best MPP for the operational conditions will be picked. This approach requires a large memory device. Interpolation and extrapolation exacerbate the problem.

2.2.2. Load Voltage/Load Current Maximization

The Load Voltage/Load Maximization approach [73,73–76] commonly uses resistive, voltage-source, current-source, or a combination of these types of loads. Figure 9 depicts the method schematically. The load current must be maximized to increase output power from voltage-source loads. To maximize power output from current-source loads, the V_{out} voltage must be maximized

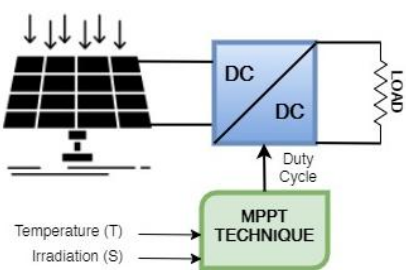

Fig. 8. Look-up Table method diagram

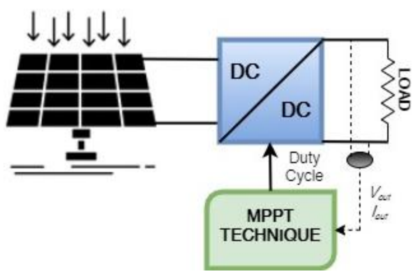

Fig. 9. Schematic of the Load Voltage/Load Current Maximization method

as well. For other loads, only I_{out} or V_{out} can be used, so only one sensor is needed. Assuming the converter is lossless, it maximizes the PV power and vice versa. No true MPP can be accomplished because the converter is deemed lossless. In the combination of voltage and current load schemes, if one parameter is taken for maximization, the second is constant.

3. Criteria on choices MPPT techniques

MPPT approaches are divided into four categories: constant parameters, trial-and-error, mathematical computation, as well as Measurement and Comparison. They are discussed in Part 1 and at the beginning of Part 2. When deciding on an MPPT technique, numerous factors must be considered, including sensors, analog/digital requirements, cost, simplicity, efficiency, and tracking speed. These factors are evaluated in this part to evaluate the previous MPPT approaches.

3.1. Sensor

The number of sensors employed in implementing of MPPT affects the decision-making process. References [13, 16–18, 20–22] also use this criterion in their review paper. Among the input and output parameters used to monitor maximum power are temperature and irradiation, as well as voltage and current. A minimum of four sensors is required. In addition to being more widely available, voltage sensors tend to be more expensive than current sensors. In order to locate the MPP, some approaches utilize a large number of sensors, while others employ a smaller number of sensors. Even with the updated approach, only a few sensors are still required.

For example, the Open-Circuit Voltage, Temperature Parametric, and P-N Junction Drop Voltage methods only use voltage sensors. Meanwhile, Short-Circuit Current uses only current sensors. Other methods that use only one sensor are the Feedback Voltage or Current method and the Load Current or Load Voltage Maximization method with one of the voltages or current sensors only. Methods other than those listed require two sensors for voltage and current, or irradiation and temperature. Methods that use irradiation and temperature sensors are the I_{MPP} and V_{MPP} Computation method and the Look-up Table method.

3.2. Analog/digital requirements

Analog or digital systems are required depending on the type of sensor needed and the ease of the MPPT approach. References [13, 16, 18–22] also use this criterion in their review paper. Analog systems are commonly used to build low-complexity approaches requiring only a single sensor. When it comes to more advanced procedures that require multiple sensors and algorithms, digital systems are the answer.

Examples of methods that can be solved with analog systems are Open-Circuit Voltage/Short-Circuit Current, Temperature Parametric, and Load Current or Load Voltage Maximization. Meanwhile, other methods are solved with a digital system apart from those already mentioned. The P&O method can be solved with an analog or digital system. However, to modify the P&O method, it is best to build a digital system.

Currently, various commercial digital systems offer convenience on the user's side. Arduino with an ATMega328 microcontroller operating with a maximum frequency of 16 MHz is suitable because it is an open embedded board with a broad community. Another microcontroller is STM32F103 which operates with a maximum frequency of 72 MHz offering better handling accuracy and MPP tracking speed. This board has 2 ADCs that can convert two analog signals at the same time, compared to Arduino Uno/Nano, which only has one. Another advantage is that it only takes one clock cycle to perform the multiplication operation. This cannot be done with Arduino. However, Arduino is user-friendly, especially for beginners, because of the broad and more familiar community than STM.

The method based on Mathematical Calculation is recommended to be built with STM32F103 because it has to perform a large number of calculation operations. Meanwhile, other methods such as P&O, DC-Link Capacitor Drop, Variable Inductance, and Look-up Table can be completed with Arduino Nano/Uno.

3.3. Cost

The cost required to build an MPPT application depends on the system features. References [13, 16, 17, 20–22] also use this criterion in their review paper. The number of sensors used and the MPPT implementation with the processing system will affect the costs involved. The need for the number of sensors and supporting circuits also affects the cost requirements. Since current sensors are relatively expensive, methods that use only voltage sensors tend to be less expensive. In addition, the pilot-PV modification method will add significantly to the cost. Analog systems are generally less expensive than microprocessor-based digital systems. On the other hand, among the microprocessor-based digital systems that have been mentioned, Arduino Nano and STM32F103 have prices that are not far apart.

3.4. Simplicity

The algorithm's simplicity in the MPPT method will affect the system used and the tracking results. Furthermore, methods with simple algorithms tend to be easier to learn for developers. References [13, 16, 18–22] also use this criterion in their review paper. The Constant Parameter-based method generally has a superior algorithmic simplicity because it does not require complicated calculations. On the other hand, the method based on Mathematical Calculations tends to have high complexity.

For example, the P-N Junction Drop Voltage method has an easy MPP tracking algorithm, which is based on the drop in the p-n junction diode voltage due to changes in the surface temperature of the PV. Meanwhile, the Differentiation method, which is based on Mathematical Calculations, with at least eight calculations that must be completed to track the MPP, makes this method have a low level of simplicity.

3.5. Stability

The stability of the MPPT method in tracking the MPP greatly affects the results of the tracking carried out. Literature [22] also uses this criterion in its review paper. Methods that have low stability tend to produce oscillations around the MPP. This oscillation occurs when the curve changes due to changes in the atmosphere and the steady-state.

For example, the basic P&O and IncCond methods yield low stability because they result in oscillations around the MPP of the step size used. Modifications made to the P&O and IncCond methods with variable step sizes can improve stability because the oscillations around the MPP can be suppressed. On the other hand, the Open-Circuit Voltage/Short-Circuit Current and Look-up Table methods do not have oscillations around the MPP when there is no change in the atmosphere. However, the tracking result point of this method is not the actual MPP point. As a result, this method cannot track the true MPP when a change in the atmosphere causes low stability. Meanwhile, modification of the Open-Circuit Voltage/Short-Circuit Current method with pilot PV can reduce this problem but causes other problems in cost.

3.6. Efficiency

Tracking accuracy is also determined by tracking efficiency. References [20–22] also use this criterion in their review paper. The standard for the amount of tracking efficiency used is (%). The MPPT method has high efficiency if it produces an efficiency close to 100%. Efficiency is given by

$$\text{Efficiency} = \frac{P_{\text{out}}}{P_{\text{MPP}}} \times 100. \tag{30}$$

With more detailed calculations, methods that use more than one measured parameter and are solved by digital systems tend to produce better efficiency. For example, the P&O method of measuring voltage and current in tracking MPP has better efficiency than the Constant Parameter-based method, which uses only one parameter. On the other hand, although both use two sensors to read voltage and current, even with digital systems, the IncCond method yields an efficiency superior to even the primary P&O method, which has been modified.

3.7. Tracking speed

Tracking speed is measured to find out how fast the system tracks the MPP when temperature changes and irradiation occurs in milliseconds (ms). References [16, 18, 19, 22] also use this criterion in their review paper. Although the Look-up Table method doesn't track the actual MPP, it has a fast-tracking speed because it only retrieves the previously saved MPP value. On the other hand, the tracking speed of the P&O and IncCond methods depends on the step size used. If the step size is large, the tracking speed is faster even though the resulting oscillation around the MPP is also greater. However, if the step size is small, the oscillation around the MPP is smaller, but the impact is a slower tracking speed.

3.8. Suitable MPPT techniques for solar photovoltaic applications

This article discusses several MPPT methods, both basic methods and modifications based on various literature, that has been discussed. It is undeniable that each of the primary methods and their modifications has advantages and disadvantages in various aspects. These aspects are what the user feels need to be considered before determining the suitable method to be implemented for their purposes. These aspects include how many and what sensors are needed, the algorithm's simplicity, and the required processing system, whether analog or digital. These aspects will affect the results in the form of stability, efficiency, and tracking speed in tracking the MPP. Furthermore, the most highlighted aspect is the costs involved in implementing the MPPT technique based on the aforementioned aspects. To make it easier for readers, Table 3 presents various aspects. The assessment of each method is based on an assessment of various literature. The assessment given uses 1.00 points as the lowest score up to 5.00 points for the highest score.

Table 3. Comparative of MPPT techniques

Method	**Sensor**	**Analog/ digital**	**Cost-effective**	**Simplicity**	**Stability**	**Efficiency**	**Tracking speed**	**Avg**
Based on Constant Parameter								
Open-circuit voltage/ Short-circuit current	V/C	Analog	**3.80**	3.40	1.67	2.60	3.40	2.97
Temperature Parametric	V		2.00	2.80	1.50	3.00	3.20	2.49
Feedback voltage or current	V/C		**4.00**	**4.00**	1.00	2.00	2.00	2.60
P-N junction drop voltage	V		**4.00**	**4.00**	1.50	3.00	**4.00**	3.30
Based on trial-and-error								
Perturb and Observe	V, C	Digital-Arduino Uno/Nano	3.40	**3.80**	3.67	3.80	3.60	**3.65**
DC-link capacitor drop	V, C		2.20	3.60	**4.00**	4.00	2.80	3.32
Variable inductance	V, C		2.00	3.00	2.50	**5.00**	3.00	3.10
Based on Mathematical Calculation								
Incremental Conductance	V, C	Digital-STM 32F103	3.40	3.00	**4.33**	4.40	3.20	**3.67**
Differentiation	V, C		2.00	2.00	**4.00**	4.00	2.00	2.80
Current Sweep	V, C		2.75	2.00	**4.00**	4.00	2.20	2.99
Feedback of power variation with V or I	V, C		2.00	2.40	**4.00**	4.00	3.20	3.12
Parasitic Capacitance	V, C		2.20	2.80	**4.00**	4.50	2.80	3.25
β method	V, C		2.00	2.80	**4.00**	**5.00**	3.50	3.45
I_{mpp} and V_{mpp} computation	I, T		2.00	3.00	2.00	3.00	**4.00**	2.80
Ripple Correlation Control	V, C		2.00	2.80	**4.67**	**4.67**	3.40	**3.51**
Based on Measurement and Comparison								
Look-up Table	I, T	Digital Arduino Uno/Nano	2.00	3.60	3.00	3.67	**4.00**	3.25
Load Voltage/Load Current Maximization	V/C	Analog	3.25	3.60	1.50	3.50	3.20	3.01

It can be seen in Table 3, the IncCond and P&O methods have high average points. It is understandable why many works of literature say these two methods are popular. The P&O method produces fairly good tracking with inexpensive but simple cost considerations. So, it has become a favorite method to be developed. On the other hand, the IncCond method is also often compared to the P&O method because of its better performance.

However, it needs to be emphasized further, the assessment criteria given still use the same average score. This means that each criterion is considered to have the same vital factors. Suppose the user wants to build an MPPT system emphasizing low cost and ignoring other criteria. In that case, the Constant Parameter-based method, especially the Feedback voltage or current method, P-N junction drop voltage, and Open-circuit voltage/Short-circuit current, is more suitable. Suppose the MPPT system to be built avoids complexity. In that case, suitable methods are Feedback voltage or current, P-N junction drop voltage, and P&O. Mathematical Calculation-based methods (except the I_{MPP} and V_{MPP} computation methods) and the DC-link capacitor drop method are suitable to be implemented in MPPT systems that prioritize stability. If efficiency is the criterion being pursued, then the Variable Inductance method, the β method, and the RCC method are the right choices. If the MPPT system being built requires a fast-tracking speed, it will be appropriate to use the P-N junction drop voltage, I_{MPP} and V_{MPP} computation or Look-up Table methods. However, referring to the initial aim of the article to obtain a suitable low-cost implementation, the IncCond, P&O, and RCC methods are superior to the average rating of the other methods.

4. Conclusion

The development of MPPT techniques to increase the output power of PV-based power plants has been a focus of many researchers to contribute to the advancement of sustainable renewable energy. Mathematical Calculation as well as Measurement and Comparison-based MPPT approaches and their adaptations have been reviewed in this paper. This paper gives an assessment to get a score on each of the criteria. Regarding the search for authors, this approach is the first to be applied to the MPPT method selection. Assessments based on criteria, such as sensors, analog/digital requirements, cost-effectiveness, simplicities, stabilities, efficiencies, and tracking speeds, are presented. The results obtained show some of the best methods based on each criterion. Furthermore, this article also finds that IncCond, P&O, and RCC are the best methods by considering all criteria. This review can be beneficial for selecting MPPT methods that can be implemented at a low cost. Furthermore, this paper can also determine the selection of the MPPT method according to specific criteria needs. The limitation of the approach used in this paper is an approach that uses a flat parameter to assess each criterion. A more in-depth study is needed to determine the percentage rating for each criterion based on priority standards for specific applications.

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