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Hill Climbing Method Based Sepic Converter for MPPT Operation of PV System

#1Asst. Prof. V. Rangavalli, #2G.Vasudevarao

1rangavallivasa@gmail.com
2g.vasudevarao.in@gmail.com

#12Department of EEE,

ANITS, Visakhapatnam, India

ABSTRACT

This paper presents a Hill climbing method (or) perturbs & observe based single-ended primary-inductor converter (SEPIC) for maximum power point tracking (MPPT) operation of a photovoltaic (PV) system. The Hill climbing method proposed presents that the convergent distribution of the membership function offers faster response than the symmetrically distributed membership functions. The Hill climbing method for the SEPIC MPPT scheme shows high precision in current transition and keeps the voltage without any changes, in the variable-load case, represented in small steady-state error and small overshoot. The proposed scheme ensures optimal use of PV array and proves its efficacy in variable load conditions, unity, and lagging power factor at the inverter output (load) side. The performance of the converter is tested in both simulation and experiment at different operating conditions. The performance of the proposed Hill climbing method based MPPT operation of SEPIC converter. The results show that the proposed Hill climbing method (or) Perturb & Observe based MPPT scheme for SEPIC can accurately track the reference signal and transfer power.

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I. INTRODUCTION

Due to its output gain flexibility, the single-ended primary inductor converter (SEPIC) acts as a buck–boost dc–dc converter, where it changes its output voltage according to its duty cycle. The selection of a proper dc–dc converter plays an important role for maximum power point tracking (MPPT) operation. The criteria for photovoltaic (PV) converter selection depend on many factors, such as cost, efficiency, flexibility, and energy flow. In this case, the flexibility represents the ability of the converter to maintain the output with the input varying, while the energy flow is assured by the continuous current of the converter. Among known converters, the SEPIC, conventional buck–boost, and Cuk converters have the ability to step up and step down the input voltage. Hence, this converter can transfer energy for all irradiation levels. Another desirable feature is continuous output current, which allows converter output parallel connection, or conversion to a voltage source with minimal capacitance. The buck or boost converters are not preferable, due to the lack of output voltage flexibility. For example, for PV system battery charging, both buck and boost converters are unable to charge the battery continuously with MPPT operation because the power–voltage curve changes with irradiation level, and hence, the voltage corresponding to maximum power changes.

There are many factors that can be considered for proposing the dc–dc converters, such as input/output energy flow, cost, flexibility, and PV array effect. Unlike a buck–boost converter, the SEPIC has a no inverted output, and it uses a series capacitor to isolate input from output [1]. The buck and buck–boost converters have discontinuous input current, which causes more power loss due to input switching. The boost converter usually has higher efficiency than the SEPIC; however, its output voltage is always larger than the input, which causes inflexibility in maximum power extraction. Both the SEPIC and the Cuk converter provide the choice to have either higher or lower output voltage compared to the input voltage. Furthermore, they have contentious input current and better efficiency compared to buck–boost and fly-back converters [2]. There is no general agreement in the literature on which one of the two converters is better, i.e., the SEPIC or the Cuk [3]–[10]. This paper seeks to use the SEPIC converter because of the Cuk converter's inverted output.

The MPPT algorithm represents optimal load for PV array, producing opportune voltage for the load. The PV panel yields exponential curves for current and voltage, where the maximum power occurs at the curve's mutual knee [11], [12]. The tracking method used, i.e., perturb and observe (P&O) [13], [14], provides a new reference signal for the controller and extracts the maximum power from the PV array.

This paper presents a Hill climbing method based MPPT operation of the SEPIC converter for PV inverter applications. As the proposed method always transfers maximum power from PV arrays to the inverter side, it optimizes the number of PV modules. The Hill climbing method for the SEPIC MPPT scheme shows high precision in current transition and keeps the voltage without any changes, in the variable-load case, represented in small steady-state error and small overshoot. As the inverter is used in a PV system, Perturb & Observe is employed for more accurate output sine wave, higher dynamic performance under rapidly varying atmospheric exploiting maximum power effectively, and improved THD**.**

II. PROBLEM OVERVIEW

Fig. 1 shows the characteristic power curve for a PV array. The problem considered by MPPT techniques is to automatically find the voltage V_{MPP} or current I_{MPP} at which a PV array should operate to obtain the maximum power output P_{MPP} under a given temperature and irradiance. It is noted that under partial shading conditions, in some cases it is possible to have multiple local maxima, but overall there is still only one true MPP. Most techniques respond to changes in both irradiance and temperature, but some are specifically more useful if temperature is approximately constant. Most techniques would automatically respond to changes in the array due to aging, though some are open-loop and would require periodic fine-tuning. In our context, the array will typically be connected to a power converter that can vary the current coming from the PV array.

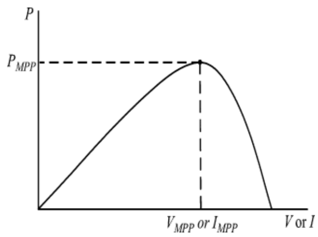

Fig. 1 Characteristic PV array power curve

TABLE I
Summary of hill climbing and P&O algorithm

Perturbation	Change in power	Next perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

A. HILL CLIMBING/P&O(PERTURB & OBSERVE)

Among all the papers we gathered, much focus has been on hill climbing [15]–[22], and perturb and observe (P&O) [23]–[39] methods. Hill climbing involves a perturbation in the duty ratio of the power converter, and P&O a perturbation in the operating voltage of the PV array. In the case of a PV array connected to a power converter, perturbing the duty ratio of power converter perturbs the PV array current and consequently perturbs the PV array voltage. Hill climbing and P&O methods are different ways to envision the same fundamental method.

From Fig. 1, it can be seen that incrementing (decrementing) the voltage increases (decreases) the power when operating on the left of the MPP and decreases (increases) the power when on the right of the MPP. Therefore, if there is an increase in power, the subsequent perturbation should be kept the same to reach the MPP and if there is a decrease in power, the perturbation should be reversed. This algorithm is summarized in Table I. In [38], it is shown that the algorithm also works when instantaneous (instead of average) PV array voltage and current are used, as long as sampling occurs only once in each switching cycle.

The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation can be minimized by reducing the perturbation step size. However, a smaller perturbation size slows down the MPPT. A solution to this conflicting situation is to have a variable perturbation size that gets smaller towards the MPP as shown in [22], [26], [29], and [36]. In [38], fuzzy logic control is used to optimize the magnitude of the next perturbation. In [34], a two-stage algorithm is proposed that offers faster tracking in the first stage and finer tracking in the second stage. On the other hand, [35] by passes the first stage by using a nonlinear equation to estimate an initial operating point close to the MPP.

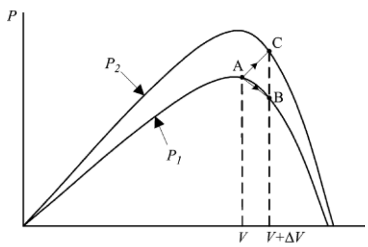

Fig. 2 Divergence of hill climbing/P&O from MPP as shown in [23]

Hill climbing and P&O methods can fail under rapidly changing atmospheric conditions as illustrated in Fig. 2. Starting from an operating point A, if atmospheric conditions stay approximately constant, a perturbation ΔV in the PV voltage V will bring the operating point to B and the perturbation will be reversed due to a decrease in power. However, if the irradiance increases and shifts the power curve from P_1 to P_2 within one sampling period, the operating point will move from A to C. This represents an increase in power and the perturbation is kept the same. Consequently, the operating point diverges from the MPP and will keep diverging if the irradiance steadily increases. To ensure that the MPP is tracked even under sudden changes in irradiance, [32] uses a three-point weight comparison P&O method that compares the actual power point to two preceding ones before a decision is made about the perturbation sign. In [36], the sampling rate is optimized, while in [38], simply a high sampling rate is used. In [22], toggling has been done between the traditional hill climbing algorithm and a modified adaptive hill climbing mechanism to prevent deviation from the MPP.

Two sensors are usually required to measure the PV array voltage and current from which power is computed, but depending on the power converter topology, only a voltage sensor might be needed as in [21] and [37]. In [39], the PV array current from the PV array voltage is estimated, eliminating the need for a current sensor. DSP or microcomputer control is more suitable for hill climbing and P&O even though discrete analog and digital circuitry can be used as in [18].

B. INCREMENTAL CONDUCTANCE

The incremental conductance (Incremental Conductance) [23], [40]–[49] method is based on the fact that the slope of the PV array power curve (Fig. 1) is zero at the MPP, positive on the left of the MPP, and negative on the right, as given by

$$dP/dV = 0, \text{ at MPP}; \; dP/dV > 0, \text{ left of MPP}; \; dP/dV < 0, \text{ right of MPP} \qquad (1)$$

Since

$$\frac{dP}{dV} = d\,\frac{(IV)}{dV} = I + V\,\frac{dI}{dV} \cong I + V\,\frac{\Delta I}{\Delta V} \qquad (2)$$

(1) can be written as

$$\Delta I/\Delta V = -I/V, \text{ at MPP}; \; \Delta I/\Delta V > -I/V, \text{ left of MPP}; \; \Delta I/\Delta V < -I/V, \text{ right of MPP.} \qquad (3)$$

The MPP can thus be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance ($\Delta I/\Delta V$) as shown in the flowchart in Fig. 3. V_{ref} is the reference voltage at which the PV array is forced to operate. At the MPP, V_{ref} equals to $VMPP$. Once the MPP is reached, the operation of the PV array is maintained at this point unless a change in ΔI is noted, indicating a change in atmospheric conditions and the MPP. The algorithm decrements or increments V_{ref} to track the new MPP.

The increment size determines how fast the MPP is tracked. Fast tracking can be achieved with bigger increments but the system might not operate exactly at the MPP and oscillate about it instead; so there is a tradeoff. In [45] and [49], a method is proposed that brings the operating point of the PV array close to the MPP in a first stage and then uses Incremental Conductance to exactly track the MPP in a second stage. By proper control of the power converter, the initial operating point is set to match a load resistance proportional to the ratio of the open-circuit voltage (VOC) to the short-circuit current (ISC) of the PV array. This two-stage alternative also ensures that the real MPP is tracked in case of multiple local maxima. In [51], a linear function is used to divide the I–V plane into two areas, one containing all the possible MPPs under changing atmospheric conditions. The operating point is brought into this area and then Incremental Conductance is used to reach the MPP.

A less obvious, but effective way of performing the Incremental Conductance technique is to use the instantaneous conductance and the incremental conductance to generate an error signal

$$e = \frac{I}{V} + \frac{dI}{dV} \qquad (4)$$

as suggested in [41] and [42]. From (1), we know that e goes to zero at the MPP. A simple proportional integral (PI) control can then be used to drive e to zero. Measurements of the instantaneous PV array voltage and current require two sensors. Incremental Conductance method lends itself well to DSP and microcontroller control, which can easily keep

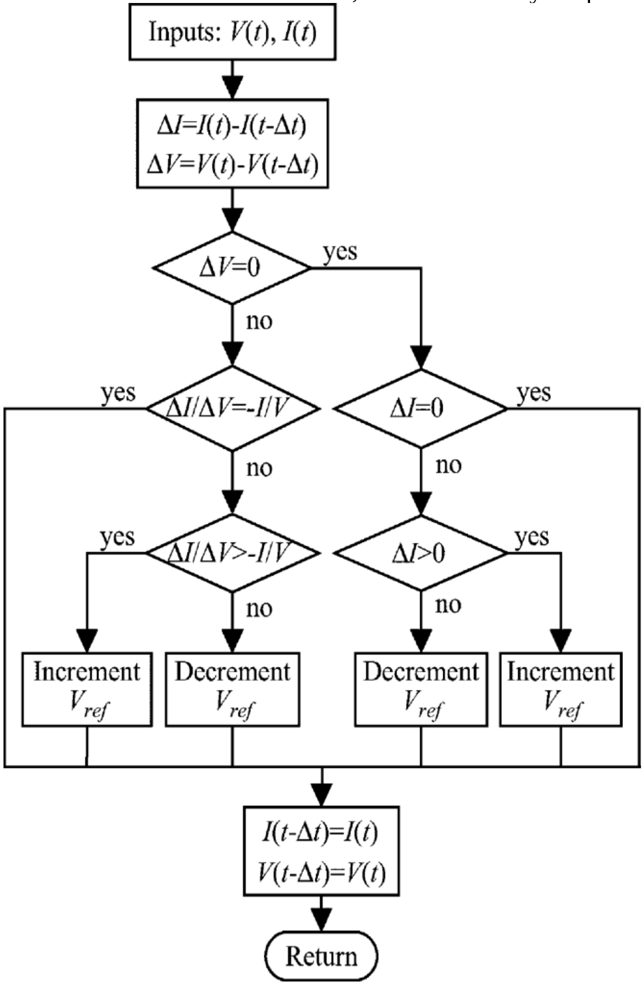

Fig.3 Incremental Conductance algorithm as shown in [43], [46], [47] and [50]

track of previous values of voltage and current and make all the decisions as per Fig. 3.

C. FRACTIONAL OPEN-CIRCUIT VOLTAGE

The near linear relationship between V_{MPP} and V_{OC} of the PV array, under varying irradiance and temperature levels, has given rise to the fractional V_{OC} method.

$$V_{MPP} \approx k_1 V_{OC} \qquad (5)$$

Where $k1$ is a constant of proportionality, since $k1$ is dependent on the characteristics of the PV array being used, it usually has to be computed beforehand by empirically determining V_{MPP} and V_{OC} for the specific PV array at different irradiance and temperature levels. The factor $k1$ has been reported to be between 0.71 and 0.78.

Once *k*1 is known, V_{MPP} can be computed using (5) with V_{OC} measured periodically by momentarily shutting down the power converter. However, this incurs some disadvantages, including temporary loss of power. To prevent this, uses pilot cells from which V_{OC} can be obtained. These pilot cells must be carefully chosen to closely represent the characteristics of the PV array. In it is claimed that the voltage generated by PN-junction diodes is approximately 75% of V_{OC}. This eliminates the need for measuring V_{OC} and computing V_{MPP}. Once V_{MPP} has been approximated, a closed-loop control on the array power converter can be used to asymptotically reach this desired voltage.

Since (5) is only an approximation, the PV array technically never operates at the MPP. Depending on the application of the PV system, this can sometimes be adequate. Even if fractional V_{OC} is not a true MPPT technique, it is very easy and cheap to implement as it does not necessarily require DSP or microcontroller control. However, points out that *k*1 are no more valid in the presence of partial shading (which causes multiple local maxima) of the PV array and proposes sweeping the PV array voltage to update *k*1. This obviously adds to the implementation complexity and incurs more power loss.

D. FRACTIONAL SHORT-CIRCUIT CURRENT

Fractional I_{SC} results from the fact that, under varying atmospheric conditions, I_{MPP} is approximately linearly related to the I_{SC} of the PV array as shown in [54], [56], and [59]–[62]

$$I_{MPP} \approx k_2 I_{SC} \tag{6}$$

Where k_2 is a proportionality constant. Just like in the fractional V_{OC} technique, K2 has to be determined according to the PV array in use. The constant k_2 is generally found to be between 0.78 and 0.92.

Measuring I_{SC} during operation is problematic. An additional switch usually has to be added to the power converter to periodically short the PV array so that I_{SC} can be measured using a current sensor. This increases the number of components and cost. In [62], a boost converter is used, where the switch in the converter itself can be used to short the PV array.

Power output is not only reduced when finding I_{SC} but also because the MPP is never perfectly matched as suggested by (6). In [60], a way of compensating k_2 is proposed such that the MPP is better tracked while atmospheric conditions change. To guarantee proper MPPT in the presence of multiple local maxima, [59] periodically sweeps the PV array voltage from open-circuit to short-circuit to update K2. Most of the PV systems using fractional *ISC* in the literature use a DSP. In [62], a simple current feedback control loop is used instead.

III.SIMULATION RESULTS

The total Simulink modal of the proposed system was as shown below

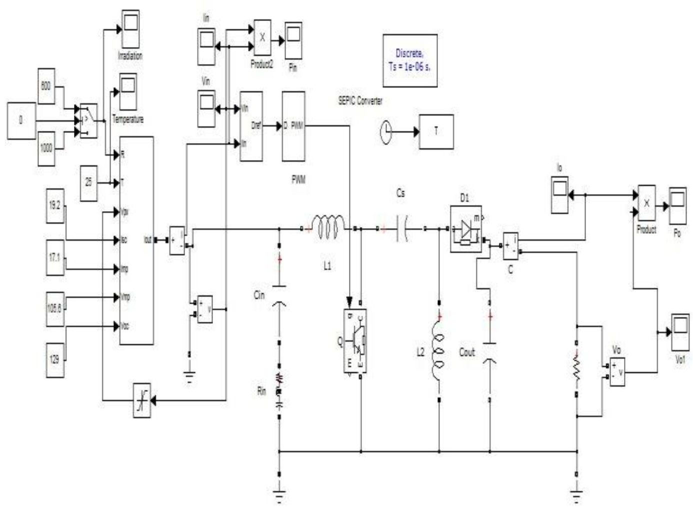

Fig.4 Simulink modal of the proposed system

The sub system simulink model of Hill climbing/Perturb & Observe shown below

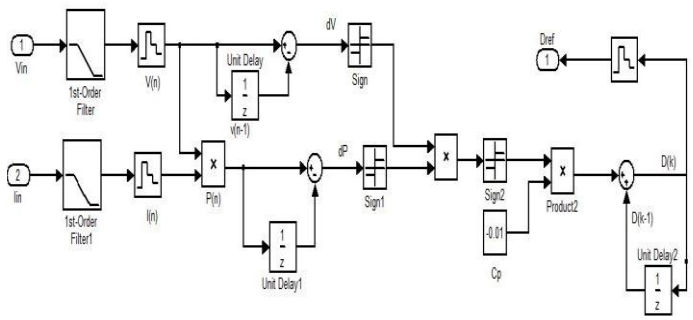

Fig.5 Simulink model of the proposed sub system system

Simulation was applied on MATLAB/Simulink to verify the practical implementation of the proposed SEPIC Hill climbing method/Perturb & Observe for the single-phase inverter. The output voltage of the proposed Hill climbing method based MPPT load conditions are shown in Fig. 6. It is noticeable that the signals were not smooth; on the contrary, they carried a component of the maximum power between voltage, current and power.

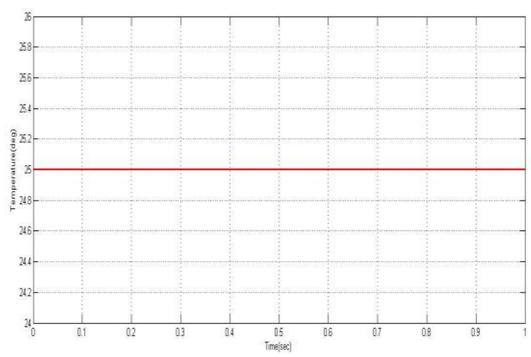

Fig. 6(a) Constant Temperature at 25 degree

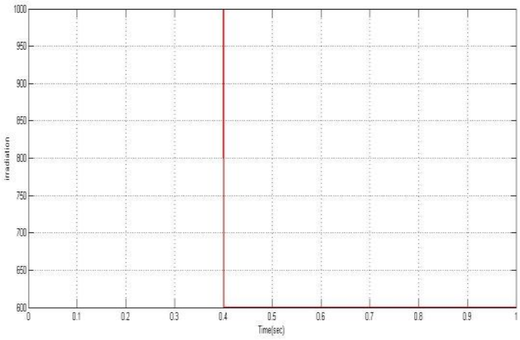

Fig. 6(b) Irradiation at 0.4 seconds

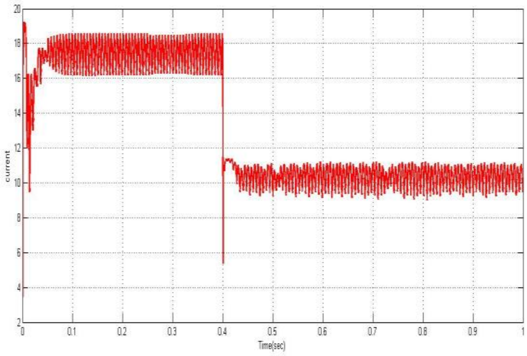

Fig. 6(c) Input current response

At initial point fig.6(c) the input current 19.5A after applying irradiation the input current settles at 9.5A at 0.4 sec.

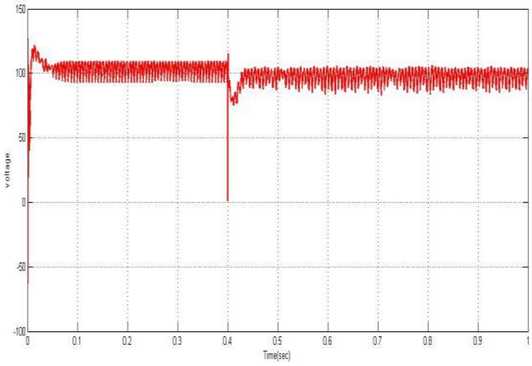

Fig. 6(d) Input voltage response

At initial point fig. 6(d) the input voltage 120V after applying irradiation the input voltage settles at 101 at 0.4 sec.

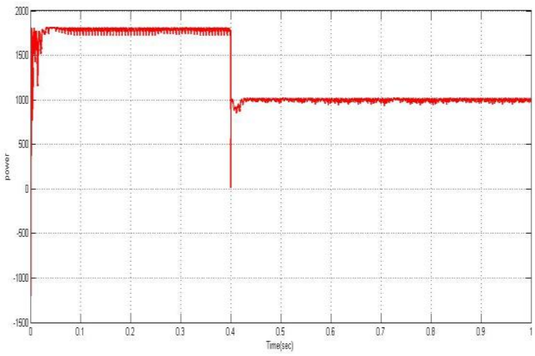

Fig. 6(e) Input power response

At initial point fig. 6(e) the input power 1800w after applying irradiation the input power settles at 1000w at 0.4 sec.

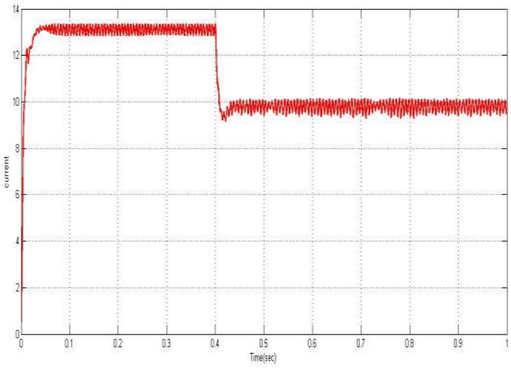

Fig. 6(f) Output current response

At initial point fig. 6(f) the output current 13.5A after applying irradiation the output current settles at 10A at 0.4 sec.

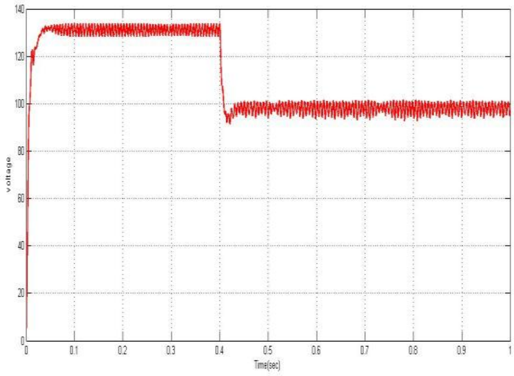

Fig. 6(g) Output voltage response

At initial point fig. 6(g) the output voltage 130V after applying irradiation the output voltage settles at 100V at 0.4 sec.

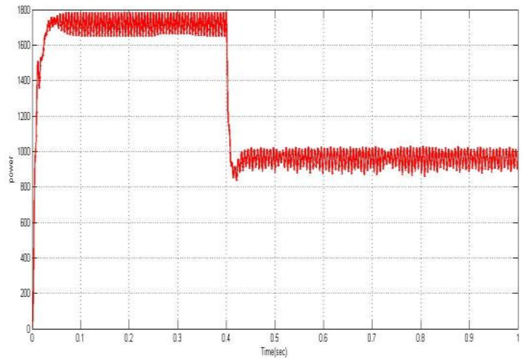

Fig. 6(h) Output power response

At initial point fig. 6(h) the output power 1800w after applying irradiation the output power settles at 1000w at 0.4 sec.

IV. CONCLUSION

Several MPPT techniques taken from the literature are discussed and analyzed herein, with their pros and cons. It is shown that there are several other MPPT techniques than those commonly included in literature reviews. The concluding discussion and table should serve as a useful guide in choosing the right MPPT method for specific PV systems.

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