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Full-length article

Comprehensive review and performance evaluation of maximum power point tracking algorithms for photovoltaic system

Asegid Belay Kebede[1], Getachew Biru Worku[2]

1. African Railway Centre of Excellence, Addis Ababa Institute of Technology, Addis Ababa, Ethiopia
2. Electrical and Computer Engineering, Addis Ababa Institute of Technology, Addis Ababa, Ethiopia

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Abstract: A photovoltaic array is environmentally friendly and a source of unlimited energy generation. However, it is presently a costlier energy generation system than other non-renewable energy sources. The main reasons are seasonal variations and continuously changing weather conditions, which affect the amount of solar energy received by the solar panels. In addition, the non-linear characteristics of the voltage and current outputs along with the operating environment temperature and variation in the solar radiation decrease the energy conversion capability of the photovoltaic arrays. To address this problem, the global maxima of the PV arrays can be tracked using a maximum power point tracking algorithm (MPPT) and the operating point of the photovoltaic system can be forced to its optimum value. This technique increases the efficiency of the photovoltaic array and minimizes the cost of the system by reducing the number of solar modules required to obtain the desired power. However, the tracking algorithms are not equally effective in all areas of application. Therefore, selecting the correct MPPT is very critical. This paper presents a detailed review and comparison of the MPPT techniques for photovoltaic systems, with consideration of the following key parameters: photovoltaic array dependence, type of system (analog or digital), need for periodic tuning, convergence speed, complexity of the system, global maxima, implemented capacity, and sensed parameter(s). In addition, based on real meteorological data (irradiance and temperature at a site located in Addis Ababa, Ethiopia), a simulation is performed to evaluate the performance of tracking algorithms suitable for the application being studied. Finally, the study clearly validates the considerable energy saving achieved by using these algorithms.

Keywords: Maximum power point tracking system, Photovoltaic, Renewable energy, Performance evaluation, System efficiency.

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Asegid Belay Kebede
Asegid Belay Kebede, assegidjesus@gmail.com

Getachew Biru Worku
Getachew Biru Worku, gbiru@yahoo.co.uk

1 Introduction

Although the photovoltaic (PV) module is an excellent source of electrical energy, it does not have very high energy conversion efficiency [1]. Its capacity to convert solar energy to electrical power is comparatively unsatisfactory, with conversion efficiency generally in the range of 12 to 25%. This range of energy efficiency is not usually achieved in practice owing to variations in the solar irradiance, temperature of the solar cell, and the electrical load [2]. Therefore, when the electrical load is coupled directly to the PV panel, the panel has to be extra-large or oversized to fulfill the power requirement of the load. This undoubtedly increases the initial investment cost of the installation. Therefore, it is always vital to run the PV cells at the maximum power point (MPP) or close to the MPP using various tracking algorithms, rather than directly connecting the load to the PV array [3].

Both the power and current outputs of the PV module rely on the terminal voltage. In addition, the variation in the solar irradiance and ambient temperature causes a significant output power fluctuation of the PV array. Consequently, this causes the operating point of the load to move very far away from the MPP of the PV array. Practically, it is not an easy task to track the true or global MPP under continuously changing source and load conditions because of the non-linear behavior of the voltage-current curve of the PV array. However, by using an appropriate maximum power point tracking (MPPT) technique, it is possible to decrease the total cost of the system and increase the output power and efficiency [4].

Figure 1 shows a typical solar energy converter consisting of a switched mode power electronics converter, the PV module, load, and MPPT device, which controls the duty cycle of the DC-DC converter.

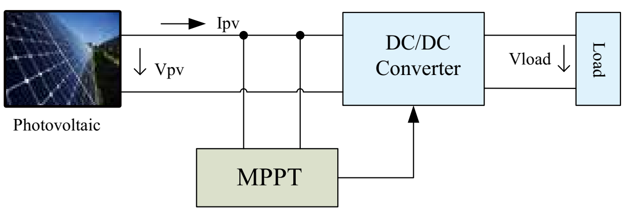

Fig. 1 DC–DC converter for PV operation at the MPP

Recently, various techniques (algorithms) have been developed for locating the MPP to increase the output power of the solar panel despite changes in the solar irradiance. However, the algorithms differ in many aspects such as hardware implementation, speed of convergence, sensor requirement, complexity, popularity, cost, and effectiveness [5]. Reference [6] examines the advantages and disadvantages of more than fifty different techniques presented in a tabular form to facilitate easy comparison. The MPPT techniques commonly discussed in literature are hill climbing (perturb and observe (P&O)), incremental conductance, fractional open-circuit voltage, fractional short circuit current, fuzzy logic control, neural network, ripple correlation control (RCC), etc. [7]. Heretofore, the P&O algorithm was the most commonly applied technique owing to its MPPT capability in comparison with other methods and its simple application of a low-cost controller. Presently, the rapid developments in the area of solar energy have resulted in more than sixty different MPPT techniques, only some of which are effective and popularly used. Considering the importance of the algorithms in increasing the energy output of the PV system, this paper comprehensively reviews the available MPPT techniques and performs a simulation on certain widely used algorithms.

2 Methodology

This paper conducts a detailed literature review of MPPT techniques using the methodology depicted in Fig. 2. While performing the review and related research, we realized that approximately seventeen algorithms are currently available in literature but only sixteen of these adopt a clear methodology and deliver reliable results. Therefore, this study evaluated and identified the most effective techniques. In addition, the commonly used MPPT algorithms were compared, and the results are presented in Section 5.

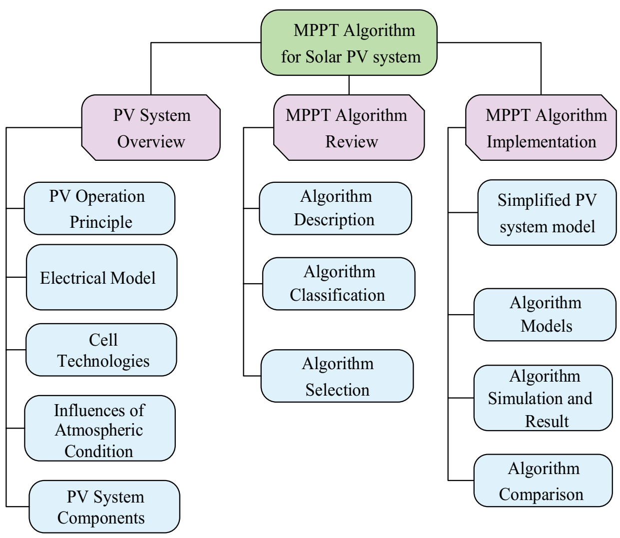

Fig. 2 Review methodology followed in this study

3 MPPT algorithms

3.1 Constant voltage method (CV)

A constant voltage technique has been implemented in the PV system to maintain the bus voltage at a nearly constant level without using a battery. It is one of the easiest and simplest techniques in tracking the MPP of the PV system. Generally, in this technique, the PV system output voltage is compared with the reference voltage, as shown in Fig. 3, and the duty cycle of the DC-DC power electronic converter is adjusted to track the operating point of the PV array at the MPP.

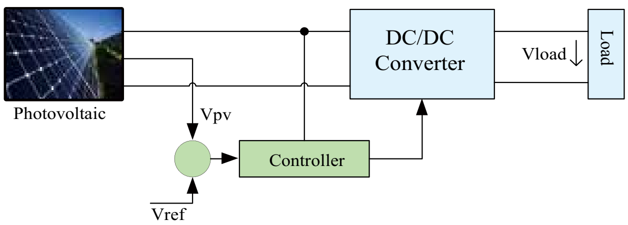

Fig. 3 Voltage feedback MPPT method with constant voltage reference

As mentioned above, this technique is very simple and economical, and it needs only one feedback loop control. However, this method does not have the capability to respond to an environmental change such as a change in the temperature or irradiation [8].

3.2 Hill Climbing/Perturb and Observe (P&O)

Hill climbing and perturb and observe (P&O) techniques are different means to realize similar goals. The P&O method involves the perturbation of the PV array operating voltage whereas the hill climbing technique involves the perturbation of the duty cycle ratio of the power electronic converter. The P&O method continuously increments or decrements the terminal voltage of the PV array and compares the trend of the output power with that of the perturbation (Fig. 4). Consequently, if the output power increases, the next perturbation must show a similar trend to attain the MPP, whereas if the output power decreases, the trend of the

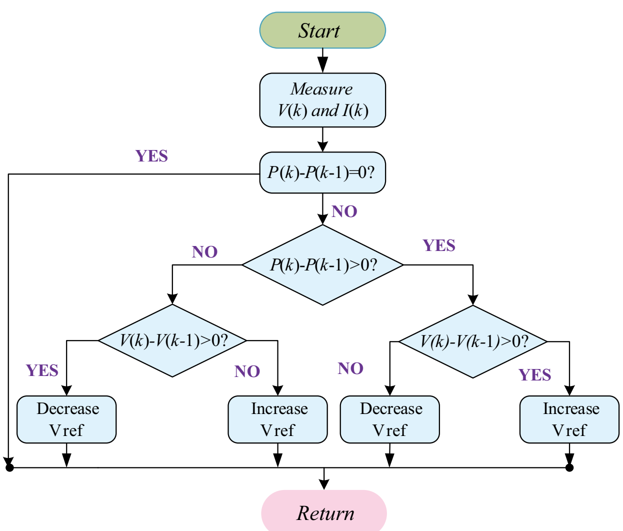

Fig. 4 Hill climbing/perturb and observe

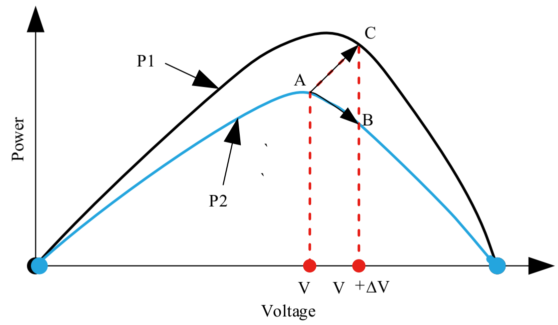

Fig. 5 Divergence between hill climbing and P&O techniques

perturbation must be reversed. This cycle (perturbation) continues until the MPP is reached.

However, the P&O technique has never attained the MPP; rather, it oscillates about the MPP. One solution to reduce the oscillation is to minimize the step size of the perturbation; however, this reduces the performance of the tracking algorithm. In [9], a varying step size perturbation is presented.

In the proposed solution, the size of the perturbation becomes increasingly smaller as it moves closer to the MPP. This solves the oscillation problem significantly and improves the speed of the MPPT. In [10], a multistage algorithm is presented. In the proposed method, the fast tracking algorithm is developed in the first stage of the perturbation. However, the Hill climbing and P&O techniques fail under changing irradiance and temperature conditions at the PV array.

As shown in Fig. 5, under a constant atmospheric condition and assuming A as the initial operating point, the perturbation continues to B. Therefore, with increase in the voltage from point A to point B, the power decreases. Then, the next perturbation reverses its direction to the opposite side (to the left of the MPP). However, if the irradiance rapidly rises within the same sampling period, the power curve changes from P1 to P2, which moves the operating point from A to C. This shift of the power point is interpreted as an increase in the power and the perturbation continues in the same direction. If the irradiance continues to change or the perturbation continues to increase, it will move further away from the MPP. In [11], a three-point weight comparison was performed for the P&O technique to evaluate and compare the true power points with two previous power points under sudden variation in the irradiance before determining the perturbation sign. In [12], the sampling rate was optimized, whereas [13] simply used a high sampling rate.

From a practical point of view, two sensors are usually required to measure the PV array voltage and current, from which the power is computed. However, depending on the power electronic converter topology, only a voltage sensor may be required, as demonstrated in [14]. In [15], the authors eliminated the requirement for a current sensor by estimating the PV array current from the voltage. Presently, a microcomputer controller or digital signal processing (DSP) is preferred in the applications of the P&O and hill climbing techniques even when the digital circuit is necessary.

3.3 Incremental Conductance

The incremental conductance (IncCond) method was first proposed by Hussein in 1996 [16]. In this technique, the derivative or gradient of the power curve of the PV module at the MPP is zero, whereas it is positive on the left and negative on the right side of the curve, as shown in Fig. 6.

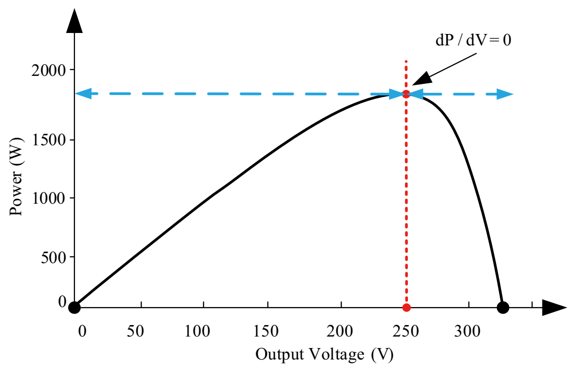

Fig. 6 Derivative of power with respect to voltage

Therefore, the MPP can be located by comparing the incremental conductance and instantaneous conductance of the PV system. The PV array is operated at the reference voltage, which has to be equal to the voltage at MPP. When the MPP is reached, the operation of the PV array will be maintained at this point until a change is observed, which is directly related to the variation in the atmospheric condition. This causes a change in the MPP. Once this change is observed, the algorithm increments or decrements the reference voltage to locate the new MPP. Fig. 7 illustrates the flow diagram of the IncCond method.

The size of the increment (decrement) determines the speed at which the MPP is tracked. Fast tracking is achieved at larger increments (decrements). However, the system will not operate precisely on the MPP; rather, it oscillates about it. Various researchers have proposed a tradeoff to avoid oscillations at large increments and slow response of the system at small increments of the reference voltage. In [17] a technique is presented to bring the operating point of the PV array close to the MPP in the first stage and then incremental conductance in the second stage. This ensures exact tracking of the true MPP in the case of multiple local maxima. In [18], a linear function is applied to divide the I-V plane into two sections. In one section, the potential MPPs are identified for varying weather conditions. This technique attempts to bring the operating point to this section and uses the method to achieve the MPP. A simple, but efficient and

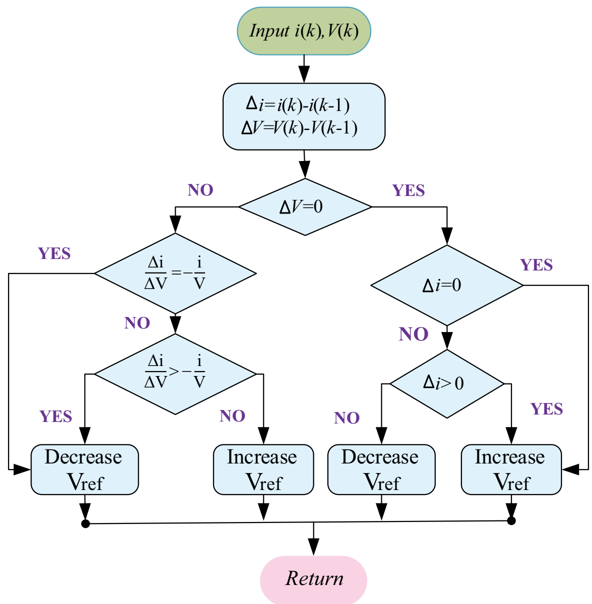

Fig. 7 Incremental conductance algorithm

effective way of performing the IncCond method is to use and to compile an error signal, as recommended in [19].

3.4 Fractional Open-Circuit Voltage

The relationship between VMPP and VOC of the PV array under varying temperature and irradiance levels is approximately linear, resulting in the fractional open circuit voltage [20].

Equation (1) shows the relationship between

$$V_{mpp} \approx K_1 . V_{OC} \tag{1}$$

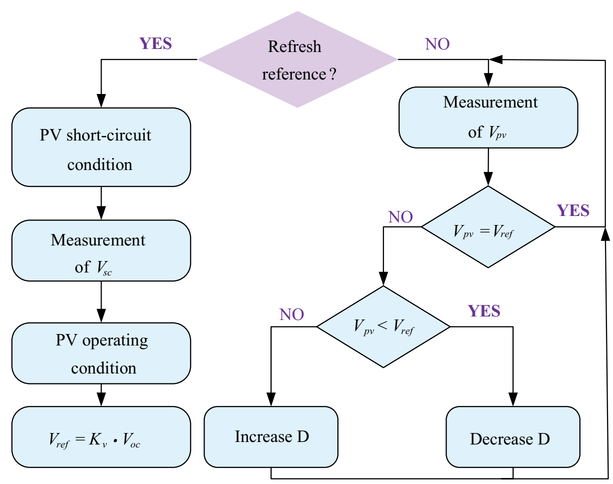

Fig. 8 Fractional open-circuit voltage

Where K_1 represents a proportionality constant, which depends on the physical characteristics of the PV module. Because this value differs for each PV array, it should be calculated beforehand; it is usually in the range of 0.71 to 0.78. Fig. 8 shows a flow diagram of the fractional open circuit voltage algorithm.

When the value of K_1 has been determined, the voltage at the MPP can be computed using (1). The open circuit voltage is measured regularly by momentarily shutting down the converter. However, this technique has some disadvantages. For example, the momentary shut down of the converter creates a temporary power loss. To avoid this, pilot cells were used in [21] to compute the open circuit voltage. However, the location and characteristics of the pilot cell must be chosen carefully to represent the PV array. Boehringer [22] presented a novel approach and claimed that the output voltage produced by the junction diode was nearly 75% of the open circuit voltage. This addressed the problem of measuring the open circuit voltage and computing the MPP voltage. A closed-loop control of the PV array power electronic converter could be applied to asymptotically attain the required voltage.

Because (1) is an approximation, the PV array does not operate at the MPP. However, this technique can be adequate depending on the application of the PV system. In addition, this technique is very cheap and easy to implement although it is not a true MPPT method. Nevertheless, under the condition of partial shade, it is no more valid, as creating multiple local maxima. In [23], a sweeping of the PV array voltage was performed to update. However, this increases the complexity of the system.

3.5 Fractional short circuit current

The fractional short circuit current technique is based on the hypothesis that the current at the MPP is related to the short circuit current in an approximately linear manner under changing atmospheric conditions, i.e.

$$I_{mpp} \approx K_{SC} \cdot I_{sc} \tag{2}$$

Where K_{SC} is a proportionality constant, which mainly depends on the fill factor and the atmospheric condition. Various researchers have confirmed that (proportionality constant) is within the range of 75% to 92%.

Fig. 9 shows the flowchart for the fractional short circuit current algorithm. Generally, this technique requires an additional switch (connected in parallel to the PV module) to measure the short circuit current of the PV system. Interestingly, an option for short-circuiting the PV array using a boost converter is presented in [24]. The additional switch discussed above can removed by using a power electronic based boost converter, where its switch could be used to shorten the PV array. When the short circuit current has been measured, the current at the MPP can be calculated using (2).

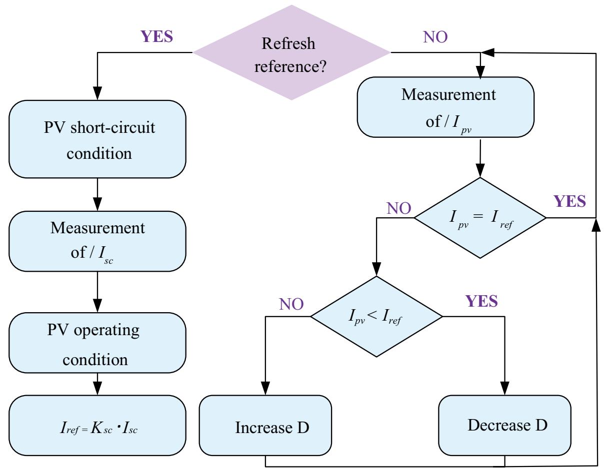

Fig. 9 Fractional short circuit current

3.6 Fuzzy Logic Control

Fuzzy logic control is one of the best MPP tracking algorithms developed over the last ten years. This technique has several advantages such as handling of imprecise input, not requiring a precise mathematical model, and management of nonlinearity [25]. The controller in this technique has three stages: fuzzification, rule based table lookup, and defuzzification. During the first stage, i.e., fuzzification, the numerical input elements are changed into linguistic elements in accordance with the membership function, as shown in Fig. 10. This case has five fuzzy levels: Negative big (NB), Negative small (NS), Zero (ZE), Positive small (PS), and Positive big (PB). Seven fuzzy levels could be used to achieve greater accuracy, as suggested in [26]. In some cases [27], the membership function can be made less symmetric to increase the importance of some fuzzy levels. The error (E) and change in error (ΔE) are the inputs to the fuzzy logic controller, and the user has several options for calculating and changing the error.

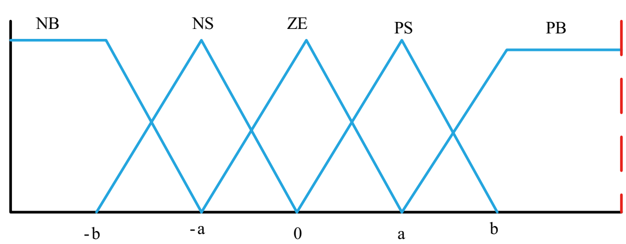

Fig. 10 Membership functions

Table 1 Fuzzy rule base table [25]

E \ ΔE	NB	NS	ZE	PS	PB
NB	ZE	ZE	NB	NB	NB
NS	ZE	ZE	NS	NS	NS
ZE	NS	ZE	ZE	ZE	PS
PS	PS	PS	PS	ZE	ZE
PB	PB	PB	PB	ZE	ZE

Once the error (E) and change in error (ΔE) are computed and changed to linguistic elements, the controller output can be looked up in a rule base table (Table 1). The linguistic element allocated to the change in the duty cycle ratio of the power electronic converter (ΔD) for various combinations of error and change in error relies on the knowledge of the user and the configuration of the converter being used. For instance, let us assume that the operating point moved to the left far from the MPP; the error (E) is now positive big and the change in error (ΔE) is zero. Then, the duty ratio, that is ΔD, should be increased to Positive Big to reach the MPP.

In the last stage, that is the defuzzification stage, the linguistic elements will be converted to numerical elements using the membership function discussed previously. This generates a signal (an analog signal) to control the power electronic converter to the MPP. It has been confirmed in various literatures that the MPPT capability of the fuzzy logic controller under changing weather conditions is very good. However, user knowledge is very important to derive the full merits of this algorithm, especially in selecting the correct error computation method and preparing the rule base table.

3.7 Current Sweep

The current sweep technique uses the sweep waveform to obtain the PV array current and update it periodically. In addition, the voltage at the MPP can be simultaneously calculated from the characteristic curve at that instant. Yu et al. [28] applied a current sweep technique using an analog system. Kobayashi et al. [29] concluded that the current sweep method is practicable if the energy consumption of the tracking system is less than the corresponding rise in energy of the entire PV system.

4 Discussion

The availability of a large number of MPPT algorithms within the industry makes it difficult for users to select the algorithm best suited to their application. Therefore, the authors have attempted to highlight the main aspects of the MPPT methods that should be considered by users.

4.1 Applications

The various MPPT methods discussed in the previous sections are suitable for numerous applications. For instance, in space satellites and orbital stations that require considerable capital, the reliability and performance of the MPPT are the most important parameters, considering its complexity and cost. In this case, the tracking algorithm must be able to constantly track the true MPP under unfavorable weather conditions without the need for periodic tuning. RCC, IncCond, and hill climbing/P&O are preferable in this case. A solar vehicle mostly requires a fast convergence algorithm. In this case, RCC, neural network, and fuzzy logic control are appropriate. In residential areas, it is important to track the MPP quickly and continuously because the main goal is to reduce the payback period. A major problem in residential areas is partial shading from other buildings and trees. In this case, the algorithm or the tracking technique must have the capability to bypass multiple local maxima. Thus, the current sweep technique and two-stage IncCond method are feasible options. The OCC technique can also be considered if the residential PV system includes an inverter. In the case of street lighting, the only requirement is to charge the battery in the PV system during the daytime, which does not require complex algorithms. Therefore, a simple and cheap MPPT algorithm such as fractional or can be implemented.

For all other applications not discussed in this section, the authors have prepared Table 2, containing the main characteristics of the MPPT methods, which can assist users in choosing an appropriate technique.

4.2 Implementation

The ease and simplicity of implementation is a significant factor in choosing the appropriate MPPT method. However, this is highly dependent on the end user's experience and knowledge. For example, some users might be more familiar with digital electric circuits, which may involve programing and the use of software. In this case, the MPPT selection might focus on fuzzy logic control, neural network, incremental conductance, hill climbing/P&O, and or feedback control. Furthermore, some MPPT techniques only apply to specific converter topologies such as OCC for DC-link capacitor droop control.

4.3 Sensors

The number of sensors needed to apply the MPPT technique to the PV system also affects the decision process.

Often, the most reliable and easiest way is to measure the voltage rather than the current. In addition, current sensors are bulkier and expensive, which makes it difficult and inconvenient to apply them to a system comprising several PV arrays with independent MPP trackers. In such cases, it might be preferable to choose algorithms that require only one sensor and can estimate the current from the voltage. Moreover, sensors that measure the solar irradiance levels, as required in, and linear current control, are not commonly available.

4.4 Multiple Local Maxima

The real hindrance to the performance of the MPPT is the existence of multiple local maxima because of partial shading of the PV arrays. In a practical scenario, tracking the local maximum instead of the actual MPP will incur a significant amount of power loss in the PV array.

As indicated before, the state based and current sweep techniques have the advantage of tracking the true MPP even under the existence of multiple local maxima. On the other hand, the other techniques need additional mechanisms, especially at the initial stage, to bypass the undesirable local maxima and bring the process closer to the true MPP.

4.5 Costs

It is challenging to determine and analyze the capital cost of each MPPT method without practically implementing it, which is beyond the scope of this paper. However, a better comparison of costs can be performed based on the software and programing requirements, type of system (digital or analog), and number of sensors used in the method. Digital methods are more expensive to implement than analog methods, which require a microcontroller that involves programing. Furthermore, removing the current sensors significantly decreases the costs.

5 Performance Evaluation

This paper is part of an ongoing research launched by Addis Ababa Institute of Technology, African Railway Center of Excellence, with the aim of generating electrical power from PV panels mounted on train rooftops. Based on a feasibility study, it was concluded that each train could generate up to a maximum of 9.5 kW of electrical power using an appropriate MPPT algorithm, which can be supplied to auxiliary traction equipment. As elaborated in section 4 of this paper, some of the significant factors for selecting a tracking algorithm are true or global maxima, PV dependence, ease and simplicity of implementation, and cost or complexity of the system. In most practical cases, the cost and complexity as well as ease and simplicity of implementation are assigned higher weights [30]. However, care must be taken not to compromise the efficiency while focusing on the cost and simplicity. Consequently, to complement the efficiency with cost and simplicity, an additional determinant comparison factor must be considered. In this regard, the convergence speed of the algorithm is the best candidate. Choosing an algorithm with low convergence speed reduces the power output of the system; similarly, high-speed algorithms obviously increase the cost of the control system. A practical guideline to reconcile the cost and complexity with efficiency is to select techniques with medium convergence speed and reasonable margin of efficiency [31]. Therefore, considering the above technical and economic reasons, the following three tracking techniques are selected to further evaluate the performance of the algorithms for their possible application to the PV panels installed on the train rooftops.

a. P&O
b. IncCond
c. Fractional Open Circuit Voltage

Table 2 Major characteristics of MPPT techniques

MPPT Technique	PV array dependent	True MPPT	Analog or Digital	Periodic tuning	Convergence speed	Implemented capacity	Sensed parameter
Hill-Climbing (P& O) [30]	No	Yes	Both	No	Varies	Low	V and I
IncCond [31]	No	Yes	Digital	No	Medium	Medium	V and I
Fractional V_{OC} [32]	Yes	No	Both	Yes	Medium	Low	V
Fractional I_{SC} [33]	Yes	No	Both	Yes	Fast	Medium	I
Fuzzy logic control [34]	Yes	Yes	Digital	Yes	Fast	High	Varies
Neural network [35]	Yes	Yes	Digital	Yes	Fast	High	Varies
RCC [36]	No	Yes	Analog	Yes	Slow	Low	V and I
Current sweep [37]	Yes	Yes	Digital	Yes	Medium	high	V and I

continue

MPPT Technique	PV array dependent	True MPPT	Analog or Digital	Periodic tuning	Convergence speed	Implemented capacity	Sensed parameter
DC link capacitor droop control [38]	No	Yes	Both	No	Fast	Low	V
Load I or V maximization [39]	No	Yes	Analog	No	Fast	Low	V and I
Array reconfiguration [40]	Yes	Yes	Digital	Yes	Slow	Medium	V and I
Linear current control [41]	Yes	Yes	Digital	Yes	Fast	High	Irradiance
OCC MPPT [42]	Yes	Yes	Both	Yes	N/A	Medium	I
Slide control [43]	No	Yes	Digital	Yes	Fast	Medium	V and I
BFV [44]	Yes	Yes	Both	Yes	Fast	High	Noise
LRCM [45]	Yes	Yes	Digital	Yes	N/A	Medium	V and I
State based MPPT [46]	Yes	Yes	Both	Yes	N/A	Low	V and I
dP/dV feedback control [47]	Yes	Yes	Digital	Yes	Fast	High	V and I
β method [48]	Yes	Yes	Digital	No	Fast	High	V and I
Array reconfiguration [49]	Yes	No	Digital	Yes	Slow	High	V and I
Lookup table method [50]	Yes	Yes	Digital	No	Fast	High	V and I
Online MPP search algorithm [51]	No	Yes	Digital	No	Fast	High	V and I
Constant voltage tracker [52]	Yes	no	Digital	Yes	Medium	Slow	V
System oscillation method [53]	Yes	Yes	analog	No	N/A	Low	V
IC Based On PI [54]	Yes	Yes	Digital	No	Fast	High	V and I
Three point weight comparison [55]	Yes	Yes	Digital	No	Fast	High	V and I
Biological swarm chasing MPPT [56]	Yes	Yes	Digital	No	Fast	High	V and I
Pilot cell [57]	Yes	Yes	Digital	No	Fast	High	V and I
Numerical method quadratic Interpolation [57]	Yes	Yes	Digital	No	Fast	High	V and I
MPP locus characterization [58]	Yes	Yes	Digital	No	Fast	High	V and I
Particle swarm optimization [59]	Yes	Yes	Digital	No	Fast	High	V and I
Piecewise linear approximation with temperature compensated method [60]	Yes	Yes	Digital	No	Fast	High	V and I
POS control [61]	Yes	Yes	Digital	No	Fast	High	V and I
Parasitic capacitances [62]	Yes	Yes	Digital	No	Fast	High	V and I
Modified Perturb and Observe [63]	Yes	Yes	Digital	No	Fast	High	V and I
Estimate, Perturb and Perturb [64]	Yes	Yes	Digital	No	Fast	High	V and I
Variable inductor MPPT [65]	Yes	Yes	Digital	No	Fast	High	V and I
Extremum seeking control method [66]	Yes	Yes	Digital	No	Fast	High	V and I
Gauss–Newton method [67]	Yes	Yes	Digital	No	Fast	High	V and I
Steepest-descent method [68]	Yes	Yes	Digital	No	Fast	High	V and I
Analytic method [69]	Yes	Yes	Digital	No	Fast	High	V and I
Newton-like extremum seeking control method [70]	Yes	Yes	Digital	No	Fast	High	V and I

continue

MPPT Technique	PV array dependent	True MPPT	Analog or Digital	Periodic tuning	Convergence speed	Implemented capacity	Sensed parameter
Sinusoidal extremum seeking control method [71]	Yes	Yes	Digital	No	Fast	High	V and I
Azab method [72]	Yes	Yes	Digital	No	Fast	High	V and I
Ripple correlation control [73]	Yes	Yes	Digital	No	Fast	High	V and I
Chaos search [74]	No	yes	Digital	No	Fast	Medium	–
Simulated annealing [75]	No	yes	Digital	No	Varies	Moderate	–
GA-optimized ANN [76]	No	Yes	Digital	Yes	Fast	High	V, T, and Ir
Temperature method [77]	Yes	Yes	Digital	Yes	Medium	Low	V and T
INR method [78]	No	Yes	Digital	No	High	Medium	V and I
Dual carrier chaos search [79]	No	Yes	Digital	No	High	Medium	V and I
dP-P&O MPPT [80]	No	Yes	Digital	No	High	Medium	V and I

5.1 Simulation results

In this section, the simulation results of the abovementioned three MPPT algorithms, namely Fractional open circuit voltages, P&O, and IncCond, are presented. The simulation is performed under the condition of rapidly changing irradiance while keeping the temperature constant because the variation of temperature is gradual compared with that of the irradiance. The solar irradiance profile applied to the PV system in this investigation is nearly realistic and demonstrates how fast each MPPT algorithm responds to the change in the stipulated profile as shown in Fig.11. Figs. 12–14 show the response of each technique to step changes in the solar irradiance. In this case, the initial value of the solar irradiance was 500 at 0 s, which increased to 1000 at t = 0.03 s. Between 0.3 s and 0.6 s, the irradiance decreased to 600, and at 0.6 s, it increased to 1000. This value was maintained until 0.8 s, after which it started decreasing to 850. The abovementioned three tracking algorithms are compared based on this variation in the irradiance. Here, the main performance comparison parameters are voltage, current, and power.

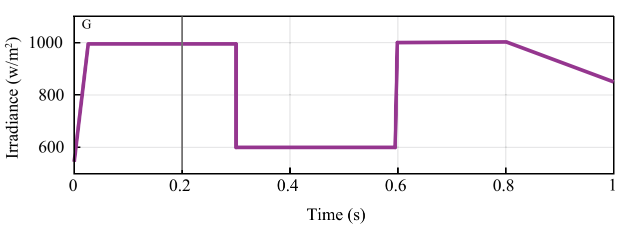

Fig. 11 Solar irradiance used in this study

5.2 Discussion

The simulation results showed that all the three MPPT algorithms were able to track the MPP under varying irradiance conditions. The following characteristics were observed:

Both fractional open circuit voltage and IncCond algorithms exhibited very good efficiency under all the examined conditions, as shown in Fig. 12 and Fig. 13, respectively, although the performance of the algorithms depended on the disturbance level.

The fractional open circuit voltage algorithm extracted slightly higher average power than IncCond under all conditions. This was attributed to the intrinsic nature of the IncCond method, which produces ripple around the MPP, leading to reduced average output power. A possible

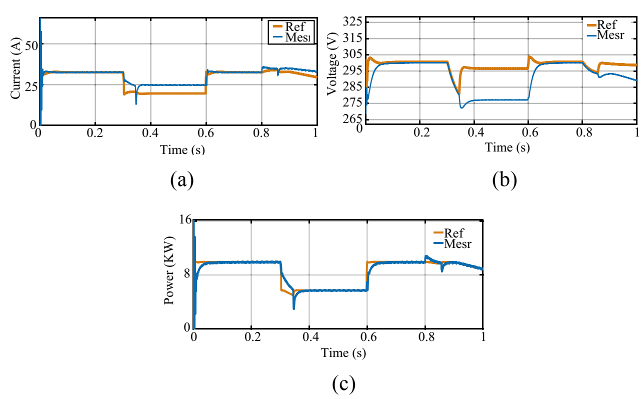

Fig. 12 Simulation results of fractional open circuit voltage: (a) Current, (b) Voltage, and (c) Power

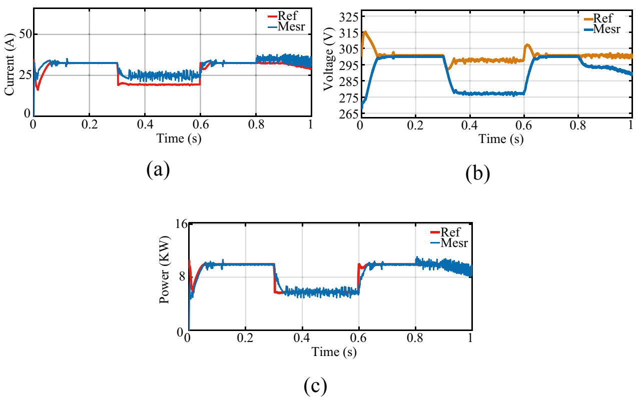

Fig. 13 Simulation results of IncCond: (a) Current, (b) Voltage, and (c) Power

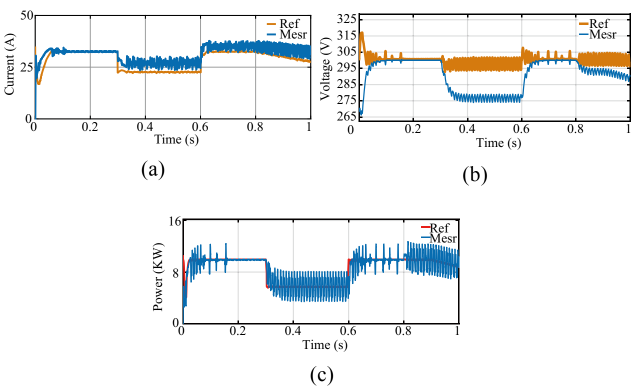

Fig. 14 Simulation results of perturb and observe method: (a) Current, (b) Voltage, and (c) Power

solution to address the ripple is to decrease the step size of the perturbation, but the size of the increment (decrement) determines the speed at which the MPP is tracked. Larger increments (decrements) result in faster tracking. However, the system will not operate precisely on the MPP; rather, it oscillates about it. Therefore, the step size of the perturbation must be reduced carefully.

Figures 13 and 14 show that the IncCond technique is superior to the P&O technique owing to the rapid fluctuation of the solar irradiance profile used in the simulation.

6 Case study

6.1 Solar potential of Addis Ababa

Various research data show that tropical regions have greater solar power resource than temperate latitudes. Europe receives approximately 1000 of average annual irradiance, whereas the Middle East receives nearly 1850. The tropical region where Ethiopia is located receives average annual irradiance of slightly more than 2000 [81]. This makes Ethiopia a perfect location for solar applications. The solar irradiance data used here are based on the Meteonorm Global Meteorological Database. The study site is located in Addis Ababa, Ethiopia. Figures 15 and 16 show the variation in the solar radiation and temperature on May 1.

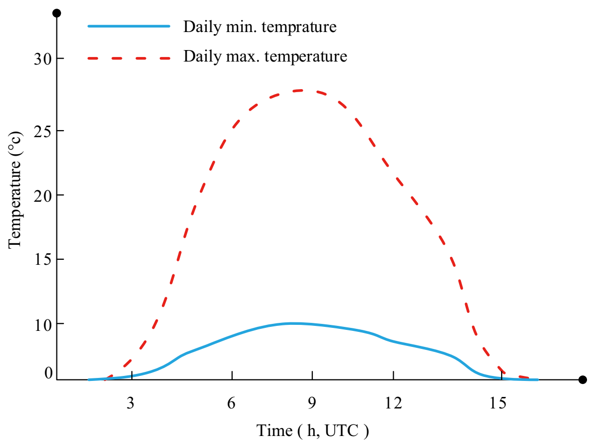

Fig. 15 Variation in temperature (May 1)

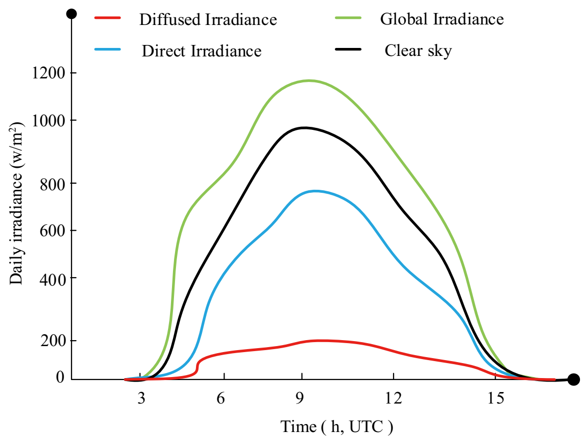

Fig. 16 Variation in irradiance (May 1)

6.2 Simulation parameters

For this study, AP6-72-320/4BB solar PV module is used and Table 3 shows the PV module parameters.

Table 3 PV module parameters used in this study

S.No	Parameters	Values
1	Maximum Power	320 W
2	Maximum power voltage	37.38 V
3	Maximum Power Current	8.56 A
4	Open Circuit Voltage	46.22 V
5	Short Circuit Current	9.06 A

continue

S.No	Parameters	Values
6	Total series cells	72
7	Total parallel cells	1
8	Ideality factor of diode	1.3
9	Cell Short circuit current temperature coefficient of Isc	0.058%/°C
10	Reference temperature	25°C
11	Solar Irradiance	1000 at STC

6.3 Hourly PV power generation

The performance of the PV module depends on the behavior it exhibits under variations in the atmospheric conditions such as irradiance and temperature. This section presents the hourly-simulated PV power of the system based on real meteorological data of the study site (Addis Ababa) exported from Meteonorm Global Meteorological Database. Only two of the superior algorithms (Section 5.2.) were considered. The meteorological condition is presented. For the simulation, the hourly meteorological data were fed to the MATLAB toolbox.

Fig. 17 and 18 show the hourly PV power generated using fractional open circuit voltage and IncCond methods, respectively. The former yields the higher power output (hourly). Numerical analysis of the simulation results shows that the fractional open circuit voltage algorithm produced nearly 4% more power than IncCond owing to the same reason discussed in section 5.2.

7 Conclusion

The global energy demand is increasing drastically due to population growth, economic development, and modernization. On the other hand, bulk extraction of fossil fuels for the production of energy has affected the adoption of renewable energy sources and threatened the development of renewable energy generation techniques. Therefore, energy efficiency of renewable energy sources must be given higher priority. In PV power generation, tracking the MPP increases the efficiency of the system significantly. This paper exhaustively presented various MPPT algorithms and compared their performance in terms of major comparison indices such as PV array dependence, true maxima, and complexity of the algorithms. In addition, to examine the extent to which the MPPT influences the production of electrical energy and evaluate the performance of the algorithms, software (MATLAB) simulation was performed on three algorithms. The results of the simulation

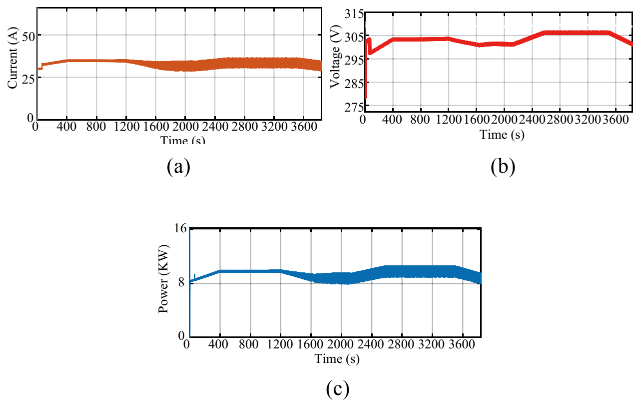

Fig. 17 Hourly PV power generation using fractional open circuit voltage algorithm: (a) current, (b) voltage, and (c) power

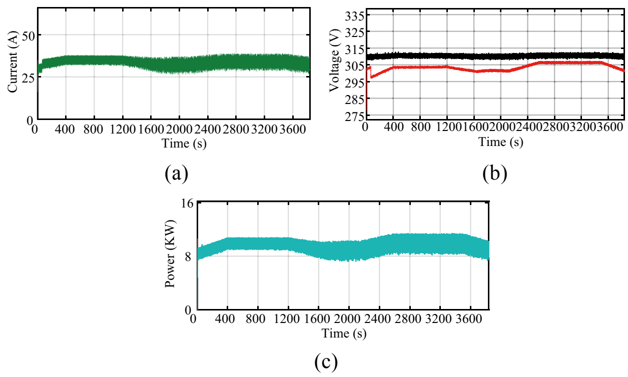

Fig. 18 Hourly PV power generation using IncCond algorithm: (a) current, (b) voltage, and (c) power

under varying irradiance condition showed the superiority of the fractional open circuit voltage over both the IncCond and P&O methods. To further evaluate the algorithms, a one-hour simulation was performed on a real meteorological environment at the selected site (Addis Ababa, Ethiopia). The results showed that the fractional open circuit method generated nearly 4% more electrical energy than the IncCond method.

The following aspects must be investigated in future studies.

PV module technology has huge impact on the power or net energy being extracted from the array. Therefore, it is possible to include these technologies and test the performance of the algorithms in different environments.

The performance of all algorithms must be tested under partial shading of the solar panel to gather more information on the appropriate choice of the MPPT technique.

8 Future research and trends

Even if the conventional or modern MPPT techniques have been effective in extracting optimum PV power for the last decades, now the trend seems shifting to hybridizing the available techniques in order to maximize the output of the PV array. Today, the hybrid MPPT algorithms showing significant advantage in exploiting the merits of the conventional (modern) techniques. In this regards, hybrid of particle swarm optimization (PSO) and artificial neural networks (ANN) methods holds the future MPPT algorithm. Here artificial neural networks is initially expected to produce values in term of power and current and then the particle swarm optimization technique, using these values generate a corresponding PV current at MPP. Consequently, this solves the hotspot challenges of the PV panel. Hybrid MPPT algorithms are most likely to dominate future researches in this particular domain.

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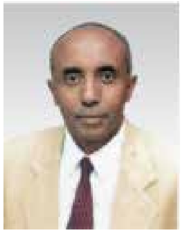
Biographies

Asegid Belay Kebede was born in Ethiopia, in 1987. He received his B.Sc. degree in Electrical Engineering from Hawassa University, in 2010 and M.Sc. degree in Electrical Engineering from Addis Ababa Institute of Technology in 2016. Currently, he is pursuing a Ph.D. degree in Electrical Engineering for the Railway system at Addis Ababa Institute of Technology, African Railway Center of Excellence. From 2010 to 2011, he was a lecturer at Debre-Berhan University. From 2013 to 2018, he has worked as a production and maintenance supervisor in Energo Transformer and Switchgear plc. Since 2019, he has been working as a technical instructor at Ethiopian airlines, Aviation academy. His research interests include electrical power system, control and renewable energy technology.



Getachew Biru Worku obtained his M.Sc. and Ph.D. in Electrical Engineering from Dresden Technical University, Germany. He has more than 25 years of academic and research experience in academic institutions and industry. He has given lectures and advised postgraduate students in electrical power in Addis Ababa University, Bahir Dar University, Adama Science Technology University and Jimma University. He has served as Dean, Department head and Academic Program Officer in Bahir Dar University and Chairman of Electrical and Computer Engineering Department in Addis Ababa University. Getachew Biru has also worked in the Aviation Academy in Ethiopian Airlines. His research areas are electrical power and renewable energy applications. He has published many papers in peer reviewed international and national journals.

(Editor Dawei Wang)