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Flexible Power Point Tracking for Solar Photovoltaic Systems using Secant Method

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Abstract—Grid-connected photovoltaic (PV) systems impose challenges like voltage fluctuations, low system inertia and power quality issues. The need to tackle these challenges led to the introduction of flexible power point tracking (FPPT), where the PV power output is controlled by an energy management system (EMS), rather than solely operating the PV systems on the maximum power point (MPP). The requirement of fast transient response implies that algorithms such as the one proposed in this paper are desirable. The proposed algorithm uses the secant method to achieve significantly improved results in comparison to the existing methods. The method also simplifies the prediction of variations during changes in the environment and power reference, hence, results in reduced oscillation around the set-point and faster convergence. Experimental validation is presented in this paper for supporting the claims. The results in terms of accuracy, convergence rate, steady state oscillations and cumulative error are bench-marked against one of the most recent FPPT methods.

Index Terms—Active power control, flexible power point tracking, grid connected photovoltaic systems, secant method.

I. INTRODUCTION

THE desire to reduce the reliance on the conventional fossil fuel resources is one of the driving forces behind the widespread utilization of renewable energy sources (RESs) for electricity generation [1]. In this regard, owing to the widespread abundance, solar energy emerges as a promising alternative [2]. Conventionally, maximum power

point tracking (MPPT) algorithms have been used to maximize the power extracted from PV systems. Various MPPT algorithms based on classical, intelligent and optimization techniques are presented in the literature, wherein the PV panel impedance is matched with the load impedance, enabling the transfer of maximum power output from the panel [3], [4]. Direct methods for tracking the maximum power point (MPP), which act during any meteorological conditions, are generally preferred. Perturb & observe (P&O) [5], [6], [7] and incremental conductance [8], [9] are the two well-known direct search methods. In some cases, novel methods such as fuzzy-logic-based MPPT control [10] and neural-network-based MPPT control [11] are also used.

These controllers are designed to operate around the MPP and can have negative effects on the grid due to the intermittent nature of the solar energy. Although the integration of PV systems with the grid has many advantages, there are many challenges in terms of voltage stability, low grid inertia, and power quality [12], [13]. The stochastic behavior of solar PV systems adversely affect the dynamic stability of the electricity grid, which has been realized by a small signal model presented in [14]. Voltage fluctuations also take place when the PV generation varies due to the environmental condition, which can create harmful effects in the grid [15].

This led to the creation of new standards and grid codes, which contain a set of recommendations and criteria for the integration of a distributed generator (DG) to the electric power system [16]. As per the grid codes, the energy management system (EMS) predicts and calculates the required active power reference for a given instance, by real time monitoring, operation and control of the power system [17], [18]. Hence, flexible power point tracking (FPPT) algorithms, which regulate the output power of the PV system to the given reference by the EMS, are proposed in the literature for providing better grid support functionalities [19].

A general algorithm for both MPPT and FPPT of PV systems was presented in [20], wherein voltage reference calculation for the active power command was performed. Constant voltage step was employed for MPPT operation as the MPPT does not change drastically for different irradiances, but the voltage step was made variable for FPPT operation based on steady state or transient operation modes. Although this resulted in faster dynamics compared to the conventional P&O method [21], it suffered from great oscillation around the set point. The algorithm was improved by employing

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adaptive voltage step in [22] by taking into account the transient and steady state part, which was further improved by including a scaling factor. An extra measurement was taken in order to discern environmental changes, which affects the PV performance. Convergence needs to be faster as the power reference may vary frequently, and the effect of environmental changes should also be considered. Hence, a more accurate root finding algorithm based on numerical methods and nonlinear searching algorithms is needed to overcome these difficulties.

A binary search-based FPPT algorithm was proposed in [23], where the search range is decided by an adaptive voltage step calculation. This method reduces the number of steps required to achieve the result, but it is more complex as, firstly, an algorithm to determine the search range is required, and then a binary search method is used to converge to the set point. Hence, an algorithm that is simpler and has a faster convergence than this one is required.

A secant-method-based FPPT algorithm is proposed in this paper to reduce the algorithm complexity and improve dynamic response for fast tracking of the set point. The main contributions of the proposed algorithm are:

- Elimination of power oscillations during the steady-state operation.
- Attainment of fast dynamics with minimal transient error.
- The secant method does not involve calculation of derivative nor evaluation of any additional function.
- There is no requirement of tuning of parameters.
- Environmental changes and active power reference changes are detected by monitoring the error in the actual power. Hence, only the memory of actual power obtained at the previous instant is required.

After detecting any such mentioned changes, this algorithm reinitiates the searching range to find the new steady-state operation point. The effectiveness of the proposed algorithm is evaluated by using an experimental setup and is compared with a recent state-of-the-art algorithm.

The rest of the paper is organised as follows. Section II provides the fundamentals of the proposed FPPT algorithm using the secant method, while its detailed implementation is provided in Section III. Section IV contains the results and detailed discussion, and Section V summarizes the main conclusions of this work.

II. PROPOSED SECANT-METHOD-BASED FPPT ALGORITHM

The fundamentals of the proposed algorithm are illustrated in Fig. 1. It can be seen that for a given power reference p^* , two possible voltages are present, one at the left side of the MPP, v_{fpp-l} , and another one at the right side of the MPP, v_{fpp-r} . Hence, through this algorithm, the operating point can be shifted either to the left- or to the right side of the MPP, depending on the predefined operating region for the PV system.

In the single stage configuration of grid-connected PV systems, the operating region is limited to the right side

Fig. 1. Principles of the FPPT operation in PV systems.

Fig. 2. Circuit diagram of two-stage PV system employing FPPT algorithm.

of the MPP, because the dc-link voltage cannot be reduced beyond a point required for grid connection. Operating at the left side of the MPP enables fast transition, but results in larger oscillations. In the two-stage grid-connected PV systems, the operating region can be extended to both sides of the MPP. The power oscillations can be reduced significantly by operating at the left side of the MPP compared to the right side. On the other hand, operating at the right side has the benefit of lower current, which results in lower ohmic losses. Operating at each side of the MPP has its own merits and de-merits, and depending on the application, the proposed FPPT algorithm provides the flexibility to choose the side of operation. Accordingly, based on the externally chosen side of operation, the proposed FPPT algorithm moves the operation point to the desired side.

The circuit diagram of a PV system employing FPPT algorithm is shown in Fig. 2. The power reference p^* , along with the side of operation, are given to the controller with the FPPT algorithm. The PV panel current, i_{pv} , and the power, p_{pv} , are also fed to the FPPT algorithm block. The tracker calculates the voltage reference, v^* , in every iteration and feeds it to the PV voltage control block to generate the switching signals for the dc-dc converter.

For the purpose of FPPT using the secant method, a reference curve is set to carry out the operation with respect to that curve, as shown in Fig. 1. The curve with the maximum power output from the solar PV for a given location is kept

Fig. 3. FPPT process using the secant method to track p^* during: (a) Right side of operation, and (b) left side of operation.

as the reference curve. During cases such as degradation of the solar panel, the PV panel power will always decrease [24], [25]. Hence, the proposed secant method for FPPT application will converge to the required solution even after panel degradation, as the operating curve will be below the reference curve defined. The power of the reference curve at the MPP is indicated as p_{m-ref}^{max} , the corresponding MPP voltage is v_{m-ref} and the open circuit voltage is v_{oc} . The region to the left of p_{m-ref}^{max} is defined to be the left of the MPP and its right is defined as the right of the MPP. The actual MPP power for the irradiance and solar cell temperature at a current instant differs from the reference, and is given by p_{m-act} , and the corresponding PV voltage is v_{m-act} . The actual power at v_{m-ref} at this environmental condition is given by p_{m-ref} , as shown in Fig. 1.

The process to be adopted for converging to the power reference using the secant method is illustrated in Fig. 3. When p^* and the side of operation are obtained, the initial parameters are set denoted by the points (v_1^0, p_1^0) and (v_2^0, p_2^0) . The line joining these two points will intersect the p^* line and the voltage at the intersection point is sent out as the voltage reference v^* , for the PV panel to operate. The equation for v^* derived from the secant method is given as

$$v^* = v_1^k + \frac{(v_2^k - v_1^k)(p^* - p_1^k)}{(p_2^k - p_1^k)}, \text{ where } k = 0, 1, 2, \dots \quad (1)$$

The PV voltage v_{pv} , obtained from tracking v^* from the previous iteration replaces v_2^k , and p_{pv} replaces p_2^k . Hence, in the next iteration, the point (v_2^0, p_2^0) is replaced by (v_2^1, p_2^1)

and the process continues. The process is similar for both sides of operation, where the only difference lies in the declaration of initial search range.

In each iteration, the error is being monitored as depicted in Fig. 3 and it is given by

$$e_k = p^* - p_{pv}. \quad (2)$$

It can be noted that for the solution to converge, the following conditions need to be satisfied:

$$|e_{k-1}| > |e_k|, \quad (3)$$

and

$$\text{Sign}(e_{k-1}) = \text{Sign}(e_k). \quad (4)$$

This process will converge to the required power reference only for the specified reference curve settings. For conditions with different operating curve, the solution may not converge when $p_{m-ref} < p^* < p_{m-act}$, as p_{m-act} will be a higher value than p_{m-ref} , and the controller considers that the p_{m-ref} itself as the maximum possible power output for the current environmental conditions. Also, there could be certain operating cases that have to be monitored and the control needs to be changed accordingly for an efficient implementation of the FPPT algorithm, as follows:

- 1) Operating in the MPP when p^* exceeds the maximum power possible from the solar PV (p_{m-act}).
- 2) Reinitialization of the search range when irradiance and the cell temperature change.
- 3) Reinitialization of the search range if p^* changes.

Detection of these operating cases, and employment of remedial measures in the proposed algorithm, are discussed in the following section.

III. IMPLEMENTATION OF THE PROPOSED SECANT-METHOD-BASED FPPT ALGORITHM

The flow chart of the proposed FPPT algorithm using the secant method is shown in Fig. 4. With reference to this flowchart, after sensing the PV parameters and the input commands, there is a check if p^* is less than p_{m-ref}^{max} to ensure that v^* is within a range where the controller is able to track it. The various operations given in the flow chart are explained in the following subsections.

At the beginning of operation, the algorithm should be initialized. The initial conditions for the proposed secant method are fixed based on the side of operation, which is given. The following values are defined when the command for operation is at the

$$\text{left side: } \begin{cases} v_1^0 = 0 \\ p_1^0 = 0 \\ v_2^0 = v_{m-ref} \\ p_2^0 = p_{m-ref} \end{cases}, \text{ and left side: } \begin{cases} v_1^0 = v_{oc} \\ p_1^0 = 0 \\ v_2^0 = v_{m-ref} \\ p_2^0 = p_{m-ref} \end{cases}. \quad (5)$$

It is to be noted that p_{m-ref} should be assigned as p_2^0 , which is unknown. Therefore, v_{m-ref} is sent out as v^* initially as shown in Fig. 5. Also, the values of v_{m-ref} and v_{oc} should be

Fig. 4. Flowchart of the proposed secant-method-based FPPT algorithm.

Fig. 5. Initialization process.

Fig. 6. Flowchart for FPPT process using the secant method.

known, and for this purpose, there are many papers available in the literature which provide mathematical equations to calculate the PV panel parameters at different irradiance and temperature [26]–[29], when the panel specifications are known. This calculation is a one-time process, which is required only in the initialization stage. Therefore, it does not have a significant effect in increasing the complexity of the proposed FPPT algorithm. A variable (*flag*) is set as 1, which is used to undergo a process to assign the initial search range with the required values as in Fig. 4, and the error (e_0) is also calculated. The *flag* is changed to 0, which enables the algorithm to continue in the normal process.

It is known that the irradiance and cell temperature do not have a significant effect on the panel voltage around the MPP [30]. Therefore, the parameters corresponding to the reference curve are selected to initiate the FPPT process. It should be noted that the issues arising from this assumption will be addressed in the following subsections of the paper.

A power tolerance, δ_p is provided as a stopping condition for the proposed FPPT algorithm. The operation ceases from going into the FPPT algorithm if $|e_k| < \delta_p$, and gives out v_{pv} as v^* . The value of δ_p is set as 5% of the MPP power value at the standard test conditions (STC). The FPPT process using the proposed secant method is shown in Fig. 6.

Considering the different operating cases mentioned in Section II, the various functions are analyzed next.

A. When p^* is Higher than p_{m-ref} :

When the p^* command is larger, in the case of left side of operation, the corresponding voltage becomes higher than

 Fig. 7. Case when $p^* > p_{m-act}$.

 Fig. 8. Flowchart for the case when p^* is between p_{m-ref} and p_{m-act} .

v_{m-ref} . Hence, from Fig. 7, it can be seen that v_2^1 has reached the left side of the MPP. Hence, this condition can be used to check whether p^* has gone beyond the maximum possible value of the panel power. If so, v^* is set as v_{m-ref} .

Similarly, if the voltage reference is found to be less than v_{m-ref} , when the side of operation was specified in the left side, one can conclude that p^* has gone greater than p_{m-act} . However, employment of an appropriate correction is required if $p_{m-ref} < p^* < p_{m-act}$, which is explained as follows:

If such a case occurs, the algorithm senses the voltage to be on the other side and operates at v_{m-ref} , which is incorrect because of two reasons:

- 1) If p^* is more than p_{m-act} , then the algorithm should operate at the MPP, which is not the case here because it gives out p_{m-ref} .
- 2) When p^* is between p_{m-ref} and p_{m-act} , then the algorithm should track the received p^* command.

To tackle these cases, the voltage difference, dv is sensed, given by

$$dv = v^* - v_{m-ref}. \quad (6)$$

This process has been depicted as a flowchart in Fig. 8. A voltage tolerance δ_v is provided to check whether the algorithm works at the MPP or not. The value of δ_v is selected as the difference between the voltage v_{m-ref} , and the voltage at which the MPP power occurs for the curve operating at the maximum possible temperature.

As depicted, there are no changes when the side of operation is left. However, during the operation at right side of the MPP, dv is sensed, and if it is less than δ_v , then the controller provides the same reference voltage calculated. Else, the

Fig. 9. Case when p^* is between p_{m-ref} and p_{m-act} .

Fig. 10. Simulation result for the temperature change from 25°C to 45°C when p^* is 930 W and the PV operates at the right side of the MPP: (a) PV power and power reference, and (b) PV voltage, and (c) performance of the proposed FPPT algorithm under variations of cell temperature.

voltage from the previous iteration is provided (which is the current PV panel voltage, v_{pv}), as the voltage reference calculated might reach the other side. Hence, the new voltage reference is given by

$$v^* = \begin{cases} v^*, & \text{if } dv < \delta_v \\ v_{pv}, & \text{otherwise.} \end{cases} \quad (7)$$

The result for the case where the temperature is increased from 25°C to 45°C (considering a worst case scenario), with an increase of 5°C every 0.2s, is presented in Fig. 10. This trend is also shown on a plot of power-voltage (P-V) characteristics in Fig. 10(c).

Fig. 11. Case when: (a) PV power is increased, and (b) PV power is decreased.

B. When the PV Power Decreases due to an Environmental Change:

Consider a condition where the power reference is in the process of being tracked down, but at this instant, the irradiance decreases or the cell temperature increases or some combination that changes the curve so that the MPP is lower than the current curve in the present operating conditions. One such case is shown in Fig. 11(a). When the irradiance has decreased, the power p_2^0 will be reflected as p_2^3 . On inspecting the error, it can be noted that

$$\text{Sign}(e_2) \neq \text{Sign}(e_3). \quad (8)$$

Hence, the range will be reset to the initial values depending on which side the power needs to be tracked down.

C. When the PV Power Increases due to an Environmental Change:

In this case, if the irradiance has increased or the cell temperature has decreased, before the arrival of the set point, the conditions will be as depicted in Fig. 11(b). It can be seen that the error value has increased from the previous one, when the irradiance increase takes place, and can be noted that

$$|e_3| > |e_2|. \quad (9)$$

This has been monitored in order to denote that an environmental change has occurred, although the reset is not required as the range of search contains the reference point which needs to be tracked down.

 Fig. 12. Case when the p^* changes.

Fig. 13. Reset mechanism.

D. When p^* Changes:

If the p^* command has changed before the current power reference has been tracked down, or after reaching the set point, the range needs to be reset again such that the reference point lies inside the search range. This can also be achieved by inspecting the error as in (4). The process is as depicted in Fig. 12.

The proposed algorithm checks if the system has encountered any of the operating cases as explained in Sections III-B, C and D. If so, the search boundary is reset, in order to contain the solution within the search range. The reinitialization of the search range to its preliminary values is as shown in the flowchart in Fig. 13.

In order to set the search boundary, p_{m-ref} should be known for the current environmental condition. Hence, similar operations carried out in the initialization process take place by setting the $flag$ as 1.

The secant method requires only simple calculations and performs fast. Besides, it does not use derivative for its calculation and hence practical feasibility is high, and any changes in the system can be easily identified and tracked by inspecting only the error.

IV. RESULTS AND DISCUSSION

In order to demonstrate the efficacy of the proposed FPPT algorithm, various test cases are considered. The parameters of the experimental setup are given in Table I. The PV panel is simulated using a Chroma 62000H-S solar array simulator and the PV panel parameters are also listed in Table I. An IMPERIX H-bridge module is used to build the dc-dc boost converter. The controller is implemented using a B BOX RCP control platform. The experimental setup is shown in Fig. 14.

To bring out the advantages of the proposed FPPT algorithm, it is compared with FPPT using adaptive-step-based P&O method presented in [22]. The parameters for the adaptive-step

TABLE I. EXPERIMENTAL SETUP PARAMETERS

Parameter	Value
Maximum PV panel power, p_{m-ref}^{max}	1 kW
Voltage at MPP, v_{m-ref}	135.8 V
Open circuit voltage, v_{oc}	173.26 V
PV side capacitance, C_{pv}	330 μ F
Boost converter inductance, L	2 mH
Switching frequency, f_s	50 kHz
DC-link voltage, V_{dc}	185 V
Calculation time-step*, T_{step}	1 s
Threshold power*, dp_{th}	40 W
$ dp/dv $ threshold*	2 W/V
Optimal value of voltage step*, V_{step-b}	2 V
Transient voltage step*, $V_{step-tr}$	Left side 5 V Right side 3 V
Scaling factor*, k_1	Left side 0.012 Right side 0.018
Scaling factor*, k_2	Left side 0.007 Right side 0.004

*For adaptive voltage step-based P&O method

Fig. 14. Experimental setup.

based P&O method are selected according to the design guidelines presented in [22], and are listed in Table I. The results of the experimental set up for various test cases are furnished. The graph of power reference p^* , actual power (p_{po} and p_{sc}), available power (p_{avai}) and PV voltage (v_{po} and v_{sc}) along with the error e_k (e_{po} and e_{sc}), are also presented. The subscript "po" refers to the adaptive-step-based P&O method and "sc" refers to the secant method in Figs. 15, 16, 17 and 18.

Further, in order to exhibit the performance comparison of these two algorithms numerically, an additional criterion, namely cumulative error (C.E.) is calculated. It is obtained by

Fig. 15. Experimental results of FPPT algorithm using the adaptive-step-based P&O and proposed secant method for step decrease in power reference at the left side of MPP operation: (a) PV power and power reference, (b) PV voltage, and (c) error.

Fig. 16. Experimental results of FPPT algorithm using the adaptive-step-based P&O and proposed secant method for step increase in power reference at the left side of MPP operation: (a) PV power and power reference, (b) PV voltage, and (c) error.

integrating the difference between the power to be tracked (p) and the PV panel power p_{pv} , and then dividing by the total energy yield, over a period of time from $t = t_0$ to $t = t_n$

given as

$$C.E. = \frac{\int_{t_0}^{t_n} |p - p_{pv}| dt}{\int_{t_0}^{t_n} |p| dt} \times 100, p = \begin{cases} p^*, & \text{if } p^* < p_{avai} \\ p_{avai}, & \text{otherwise.} \end{cases} \quad (10)$$

p is defined as $\min\{p^*, p_{avai}\}$, as the controller will track the available power p_{avai} , when p^* exceeds the maximum power output possible from the PV.

A. Experimental Step Change in Power Reference Test

A step change in p^* is sent as a command to the FPPT algorithms to observe their tracking efficiency. The panel is operated at 1000 W/m^2 and 25°C cell temperature.

The case when a step decrease in p^* is given, with the command to operate at the left side of MPP, is shown in Fig. 15. The power reference p^* is decreased from 1000 W to 500 W at $t = 0.05$ s. It can be observed that the secant method settles at $t = 0.135$ s and the adaptive-step-based P&O method at $t = 0.21$ s. The error plot in Fig. 15(c) shows that the adaptive-step-based P&O has a steady state error of up to 40 W at a few instances, whereas it is less than 5 W in the case of the secant method. Also, the C.E. is as high as 13% in the case of adaptive step P&O method, whereas it is only 5.86% in the secant method.

Another condition when a step increase in p^* is given, with the command to operate at the left side of MPP, is shown in Fig. 16. The power reference p^* is increased from 450 W to 900 W at $t = 0.05$ s. The secant method settles at $t = 0.16$ s and the adaptive-step-based P&O method at $t = 0.27$ s. The error plot in Fig. 16(c) shows that the adaptive-step-based P&O has a steady state error up to 10 W at few instances, whereas it is less than 3 W in the case of the secant method. Adaptive step P&O has a C.E. of 5.67%, whereas the secant method has a C.E. of only 4.67%.

The C.E. after reaching the steady-state while employing the secant method is 0.23% and 0.21% for a step change in power reference at the right side and the left side of the MPP operation, respectively, whereas the corresponding values when the adaptive step P&O algorithm is used are 2.1% and 0.41% for a step change in power reference at the right and left sides of operation, respectively, when adaptive-step-based P&O algorithm was used. The steady-state C.E. in the secant method is the constant error in actual power e_k , and not because of the oscillatory error as in the case of the adaptive-step-based P&O method. The C.E. during the transient state while employing the secant method is 27.29% and 19.22% for a step change in power reference at the right and left sides of operation, respectively, whereas when the adaptive-step-based P&O algorithm is used, the corresponding values are 54.02% and 22.56% for a step change in power reference at the right and left sides of the MPP operation, respectively. The various performance parameters for the comparison of the secant method and the adaptive voltage-step-based P&O algorithm are given in Table II.

TABLE II. PERFORMANCE PARAMETERS OF FPPT ALGORITHMS FOR STEP CHANGE IN POWER REFERENCE

FPPT Algorithm	Step decrease in p^* - right			Step increase in p^* - left		
	C.E. (%)		Settling Time (s)	C.E. (%)		Settling Time (s)
	Steady-state	Transient		Steady-state	Transient	
Conventional Adaptive P&O	2.1	54.02	0.21	0.21	22.56	0.27
Proposed Secant Method	0.23	27.29	0.135	0.41	19.22	4.67

Fig. 17. Experimental results of FPPT algorithm using the adaptive-step-based P&O and proposed secant method for variable change in power reference at the left side of MPP operation: (a) PV power and power reference, (b) PV voltage, and (c) error.

Hence, it is evident that the FPPT algorithm using the secant method is more efficient than the adaptive-step-based P&O method. The settling time in the secant method is about half the settling time of the adaptive-step-based P&O method. There are no oscillations around the set point in the secant method, whereas the adaptive-step-based P&O method continues oscillating even after reaching the set point. Also, adaptive step P&O gives high C.E. on the right side of operation, which is not the case in the secant method.

B. Experimental Variable Change in Power Reference Test

The power reference, p^* , is being changed at different intervals. The command from the EMS can change depending on the demand, weather and the conditions of the physical elements present. Hence, it may stay constant for some period, demand a step change or a linearly varying p^* can be commanded. Both algorithms are subjected to the following changes:

The panel is operated at 1000 W/m^2 and 25°C cell temperature. Initially, $p^* = 800 \text{ W}$ is given as an input as

Fig. 18. Experimental results of FPPT algorithm using the adaptive-step-based P&O and proposed secant method for variable change in irradiance at the: (a) Right side of MPP operation, and (b) left side of MPP operation.

in Fig. 17. At $t = 5 \text{ s}$, p^* is decreased to 350 W. At $t = 10 \text{ s}$, a step increase of 900 W is given. Then, p^* is decreased linearly from 900 W at $t = 15 \text{ s}$ to 450 W at $t = 25 \text{ s}$, and it stays there till $t = 30 \text{ s}$. The power reference p^* is then linearly increased from 450 W at $t = 30 \text{ s}$ to 1200 W at $t = 35 \text{ s}$, and stays there till $t = 40 \text{ s}$. The panel cannot give out 1200 W because the maximum output power possible at specified conditions is 1000 W. Hence, the algorithms operate on MPP. Finally, a step decrease of $p^* = 500 \text{ W}$ is given and the algorithms revert back to FPPT.

It can be seen that the secant method gives fast tracking of the reference. Even during the linear change of power reference, the error is quite small. The C.E. for the adaptive step P&O method is 4.5% and for the secant method is 3.54%. When the power reference exceeds the available power, the secant method operates at MPP without any oscillation, but the adaptive-step-based P&O method shows a power oscillation around the MPP of about 150 W.

C. Experimental Variable Change in Irradiance Test

In this case, the irradiance is varied while the power reference remains constant. This is prone to take place due to the intermittent nature of solar energy. Results are presented for both the sides of operation under following conditions: The power reference p^* is set to 700 W and the command is given so as the panel operates in the left side of MPP. From $t = 0 \text{ s}$ to $t = 10 \text{ s}$, the irradiance is set to 400 W/m^2 .

TABLE III. OVERALL CUMULATIVE ERROR FOR FPPT ALGORITHMS

Test case	Side	Overall C.E. (%)	
		Conventional Adaptive P&O	Proposed Secant
Step p^* (decrease)	right	13.07	5.86
Step p^* (increase)	left	5.67	4.67
Variable p^*	left	4.5	3.54
Variable irradiance	right	5.66	3.17
	left	6.01	3.12

In this case, the maximum power that can be extracted from the panel is only 400 W. Hence, it can be seen from Fig. 18 that both the algorithms give out the available power from the PV. At $t = 10$ s, the irradiance is increased linearly until it reaches an irradiance of 1000 W/m^2 at $t = 20$ s. When the available power increases to 700 W or above, the algorithms track the power reference command given. The irradiance stays at 1000 W/m^2 until $t = 30$ s. Then, the irradiance is decreased linearly to 400 W/m^2 at $t = 35$ s and stays there further. Once the available power becomes less than the power reference, the algorithms operate at the maximum power point to give out the available power.

The secant method tracks the power reference with minimal error, with a C.E. of 3.17% and 3.12% during left side and left side of operation respectively. When the power reference becomes more than the available power, the algorithm tracks the MPP. The P&O method has a C.E. of 5.66% when side of operation is at the right, and about 6% when the operating side is left. During the linear change of irradiance, the secant method has a step change in power every 1 s. During the MPP operation, it exhibits less ripple than the adaptive step P&O method.

The C.E. for both the algorithms under various test cases as described are given in Table III. It can be seen that the secant method showcases better performance on both sides of operation than the adaptive step P&O method.

D. Simulation Over a Day

In order to showcase the efficacy of the proposed secant-method-based FPPT algorithm, the control algorithm is simulated over a day. For this purpose, Sydney, Australia is selected as a site (Latitude: $-33^\circ 52' 12''$, Longitude: $151^\circ 12' 0''$, Altitude: 42 m above sea level), where the PV is installed. The PV parameters as in Table 1 are used for this purpose. The irradiance data has been obtained from Meteonorm 7.3, from the PVsyst software.

An irradiance profile of a day with an average clearness index of 0.3 is selected. Two different power references were chosen as $p^* = 500 \text{ W}$ and $p^* = 300 \text{ W}$. The PV is operated at the left side as shown in Fig. 19. The C.E. (calculated when p^* is less than the available power, p_{avai}) when $p^* = 500 \text{ W}$ is 0.17% and when $p^* = 300 \text{ W}$ is 0.14%. The controller action can be examined from the plot of power-voltage (P-V) characteristics of the PV system, over a range of varying

Fig. 19. Simulation results of FPPT algorithm using the proposed secant method for a day with an average clearness index of 0.3: (a) PV power and power reference, (b) PV voltage, and (c) variation of PV panel power and voltage for different irradiance values.

irradiance as in Fig. 19(c). It can be noted that irrespective of the changes in irradiance over 24 hrs, the performance of the algorithm is not affected.

E. Discussion

The advantages of the secant-method-based FPPT algorithm over the FPPT algorithms available in the literature can be clearly discerned from Table IV. The convergence rate of the proposed secant method is superlinear, which is faster than the conventional methods, which have a linear and logarithmic order for the number of iterations required for convergence [23], [31], [32]. Also, there is no requirement for tuning of parameters in the proposed secant method, whereas it is required in the case of the conventional adaptive-step-based P&O algorithm (scaling factors (k_1 and k_2) and the voltage step (V_{step-b} and $V_{step-tr}$)) and the binary search method (base voltage, v_b) in order to achieve optimized results. In the secant method, only the value of p_{pv} is required from the previous instance, but in the conventional algorithms, several values from the previous instance are required. Finally, in the proposed secant method, the search boundary is fixed, whereas in the binary search method, a separate algorithm is required

TABLE IV. COMPARISON BETWEEN DIFFERENT FPPT ALGORITHMS

FPPT Algorithm	Conventional Adaptive P&O [22]	Binary Search [23]	Proposed Secant Method
No. of iterations (n) /	$n = (N+2)(N-1)/2N^*$	$n = \log_2 N^*$	$R = 1.618$ [31], [32].
Convergence Rate (R)	- Linear	- Logarithmic	- Golden ratio (Superlinear)
Tuning of parameters	Required	Required	Not required
Parameters required from previous instant	$\Delta v_k, \Delta p_k$	$\Delta v_k, e_k (\Delta p_k), \Delta e_k$	$e_k (\Delta p_k)$
Power oscillations in the steady state	Present	Absent	Absent
Setting of search boundary	Not required - Only a point is needed	Requires a separate algorithm for fixing the search boundary	Fixed search boundary - 0 to v_{m-ref} (or) v_{m-ref} to v_{oc}

*N - Number of elements in the data-set.

to fix the search boundary.

V. CONCLUSION

An algorithm for FPPT operation of solar PV system based on the secant method has been proposed. The flowchart presented for illustrating the implementation of this algorithm shows that it is simple to adopt and covers all possible cases that might arise during the operation of a PV system, starting from the initialization process. The proposed method has been demonstrated with experimental results and bench-marked against the most recent adaptive voltage step-based P&O algorithm. From the study of these results under various operating situations, such as step change and linear change in power reference and also during change in irradiance, it is observed that the secant method provides much faster settling times compared to the adaptive-step-based P&O method. Moreover, by adopting the proposed method, the set power reference is regulated accurately and the power oscillations are completely eliminated. This is due to the fact that this proposed algorithm ceases its operation only when the error between the reference and actual power is less than the specified tolerance. Results were also presented after simulating the PV system over a day, with the proposed FPPT algorithm. The cumulative error is very minimal on all the test conditions for the proposed method on both sides of operation compared to the adaptive voltage step-based P&O method. Its execution is also simple, as there is no need for evaluating any derivatives or additional functions. Also, by monitoring only the error value, any change in the system is identified and the algorithm reverts back to its initial values. Overall, the proposed secant-method-based FPPT algorithm showcases better performance than any other FPPT algorithm available in the literature.

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