

Review

Performance Evaluation of PV Model-Based Maximum Power Point Tracking Techniques

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Abstract: Maximum power point tracking (MPPT) techniques extract the ultimate power from the photovoltaic (PV) source. Therefore, it is a fundamental control algorithm in any PV configuration. The research in this area is rich and many MPPT methods have been presented in the literature. However, in the current study, we focus on the PV model-based MPPT algorithms. In this regard, the classification of this category can be mainly divided into curve fitting methods and techniques based on the mathematical model or characteristics of the PV source. The objective of the PV model-based MPPT algorithm is to allocate the position of the maximum power point (MPP). Thus, no searching efforts are required to capture that point, which makes it simple and easy to implement. Consequently, the aim of this study is to give an overview of the most commonly utilized model-based MPPT methods. Furthermore, discussion and suggestions are also addressed to highlight the gap in this area. The main methods from the literature are compared together. The comparison and evaluation are validated using an experimental hardware-in-the-loop (HIL) system, where high efficiency (more than 99%) can be obtained with a simple calculation procedure and fast convergence speed.

Keywords: PV systems; maximum power point tracking; review; PV model-based maximum power point tracking



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1. Introduction

Nowadays, renewable energy sources are getting significant interest [1,2]. Numerous factors have contributed to gaining such importance. However, the environmental issues of the conventional sources are considered the main engine for many countries to adopt renewable energies [2,3]. Among these sources, photovoltaic (PV) energy is becoming a preferable source due to the suitability of stand-alone and grid-connected applications [3]. This, in turn, contributes to the fast increase and development of the PV industry [4]. As a result, the PV applications include different converter topologies to adapt to the variety of PV applications, in which several converters are utilized. For example, step-up converters (boost) are preferred for grid-tied purposes, and step-down converters (buck) are utilized for battery charger applications [5,6].

The PV source exhibits a nonlinear characteristic, which implies an existence of a unique peak point under uniform radiation condition [7]. Therefore, the goal of the maximum power point tracking (MPPT) scheme is to track that point at any operating condition [8]. Obviously, the location of the maximum power point (MPP) varies according to the atmospheric conditions, namely the radiation and temperature. Different MPPT techniques have been discussed in the literature [9–12]. However, the main classification can be concluded as follows:

- Searching-based MPPT: In this category, the MPPT technique is trying to pursue the MPP based on exploration. To be specific, these methods depend on the previously mentioned fact that there is only one peak of the power-voltage (P-V) characteristic. Further on, the slope of that curve is positive on the left side of this point and negative on the right side [13]. The most popular techniques in this section are the perturb and observe (P&O) and incremental conductance (INC) methods [14–16]. Furthermore, several modifications are developed to enhance the behavior of such methods, especially the remarkable oscillations at steady-state and slow transient response [17,18].
- PV model-based MPPT: Generally, the model-based MPPT is concerned with the characteristics of the PV source at different atmospheric conditions of temperature and radiation. Therefore, the main objective of this group is to find a relation between the MPP and the variable operating conditions [19]. In this regard, and commonly, the fractional open-circuit voltage and fractional short-circuit current methods are utilized [20].
- Intelligent MPPT techniques: In this branch, artificial neural network (ANN) and fuzzy logic controller (FLC) are employed [21]. However, these techniques require a lot of training and tuning efforts [22]. Recently, model predictive control (MPC) is gaining attention, and it can be classified within this group of MPPT. The MPPT-based MPC depends on the discrete-time model of the PV system, where the switching action is obtained using a predefined cost function [2]. The cost function determines the optimal switching state according to the difference between the reference and the predicted control parameter. Clearly, the MPC technique needs high computation power due to the prediction stage [23]. Furthermore, sliding mode control is also discussed in the literature, which presents numerous advantages such as precise tracking behavior and robustness to parameter variations [24,25]. However, the chattering problem is the main drawback of this control algorithm [26].
- MPPT algorithms for partial shading: There are situations where the PV source is partially shaded. For instant, clouds and nearby buildings can cause shadowing on some modules in the PV source (array) [27]. This, in turn, makes the characteristics of the PV generator have several peaks, where one of them is the global maximum. Therefore, the purpose of such methods is to distinguish this global point from others. Modified versions of the P&O and INC methods are presented to tackle the issue of partial shading [28,29]. These techniques provide increased efficiency in comparison with the original versions with a low calculation load. However, they may fail to track the global power at complex partial shading patterns [30,31]. Consequently, meta-heuristic and bio-inspired techniques are commonly used to track the ultimate and global point such as particle swarm optimization (PSO), genetic algorithm, gray wolf optimization, etc. [32,33]. Several modifications are suggested to improve the performance of the optimization techniques, where a fast and adaptive technique is proposed in [34], to address the problems of the original PSO. Similarly, the issues associated with the cuckoo search algorithm are discussed and solved in [35]. Further on, the development of the optimization techniques is still ongoing, where more recent strategies are utilized to further improve the MPPT performance concerning the efficiency and tracking speed, for example, bat and musical chairs algorithms [36,37]. The main drawbacks of these methods (optimization-based approaches) are the complex implementation and the need for high computational burden. Therefore, and from a practical point of view, the optimization methods are not preferred for execution in the PV industry [31,38].

In light of the above, the PV model-based approaches are considered the most effective methods for MPPT, where these methods are simple to implement [39]. Furthermore, they consider the variation of the atmospheric conditions. Therefore, there is no confusion or divergence, as in the case of the searching-based techniques [18,40]. Moreover, there is no need for a high computational capability of real-time controller, which makes it more

proper for low-cost applications [41]. This encourages the authors to highlight the main PV model-based MPPT techniques. In the literature, very simple models, in addition to more sophisticated algorithms, are covered. Thus, the authors are motivated to investigate the PV efficiency under different methods and use the same setup for testing. Furthermore, discussion and suggestions for efficiency improvement are also explored. In conclusion, the contribution of this work is summarized as follows:

- Providing a review of the most popular PV model-based MPPT techniques.
- Experimental evaluation of the main model-based MPPT methods using HIL implementation.
- The experimental validation considers a variety of atmospheric conditions and profiles (static and dynamic), which is considered a big merit of the HIL implementation and contributes to a better evaluation of the performance of the PV system even under worst-case scenarios.
- Comparison and discussions to highlight the differences among these methods. Furthermore, some key suggestions are presented.

The remainder of this article is arranged as follows: Section 2 gives the mathematical model of the PV system under study. The main PV model-based MPPT techniques from the literature are presented in Section 3. The experimental evaluation and comparison are discussed in Section 4. Discussions on the model-based schemes are extended in Section 5. Finally, the paper is finalized in Section 6.

2. Model of the PV System

2.1. Model of the PV Source

Numerous models are used to represent the PV source's characteristics. However, the most utilized model is the single-diode one, which is known for its accuracy, simplicity, and moderate computational effort [42]. The objective of this model is to characterize the PV source at different atmospheric conditions of radiation and temperature. Therefore, the current-voltage (I-V) characteristics of the single-diode model are described as [42,43]:

$$i_{pv} = i_{ph} - i_0 \left[e^{\left(\frac{v_{pv} + i_{pv} R_s}{n N_s v_t} \right)} - 1 \right] - \frac{v_{pv} + i_{pv} R_s}{R_{sh}}, \quad (1)$$

where i_{ph} is the photovoltaic current, i_0 is the diode saturation current, n is the diode ideality factor, R_s is the PV module series resistance, R_{sh} is the PV module shunt resistance, N_s is the number of cells in one module, i_{pv} is the output current, and v_{pv} is the output voltage. Popularly, the characteristics of the PV source at different atmospheric conditions are used to describe its behavior [2]. To obtain these characteristics, the parameters of the single-diode model need to be identified. The single-exponential model has five parameters, namely, the photovoltaic current, the diode saturation current, the ideality factor, the series resistance, and the shunt one. Numerous formulations are provided in the literature for the photovoltaic and saturation currents [44,45]. To estimate the rest of the parameters (n , R_s , R_{sh}), analytical methods or optimization-based algorithms can be used. In the analytical category, normally, three equations (for three unknown parameters) are derived and solved by iterative techniques (for example, Newton–Raphson method). Generally, the open-circuit point, short-circuit point, the maximum power one, and the slope of the characteristics at such points are used to obtain these equations [44]. For the optimization techniques, the characteristics provided in the data-sheet or experimentally are employed in the optimization function, where the objective or cost function is to obtain the characteristics such that the error between the produced curves and data-sheet ones is minimized as much as possible. Numerous factors are utilized to optimize the cost function such as root mean square error and absolute error [46]. Recent approaches are employing supply demand optimizer [47], heap-based algorithm [48], turbulent flow of water optimizer [49], and gorilla troops method [50]. Despite the precision of the optimization methods in comparison with numerical techniques, they suffer from high computational load and

frequent parameter tuning [51]. Furthermore, in high-dimensional models, they can be easily trapped at local solution [47].

2.2. Boost Converter Model

As discussed earlier, different converter topologies are utilized in the PV system based on the application. However, the boost converter is chosen here for implementation. The model of the boost converter relies on the action of the power switch in the circuit. Therefore, two modes of operation describe the behavior of the boost converter. The modes of operation are shown in Figure 1. This can be simply formulated by [2]:

$$\begin{aligned} \dot{x} &= \mathbf{A}x + \mathbf{B}u, \\ y &= \mathbf{C}x + \mathbf{D}u, \end{aligned} \tag{2}$$

where $x = [i_{pv} \ v_c]^T$ is the state vector, $u = v_{pv}$ is the input voltage, and $y = v_c$ is the output voltage. Furthermore, \mathbf{A} , \mathbf{B} , \mathbf{C} , and \mathbf{D} are the system matrices and are structured as:

$$\mathbf{A} = \begin{bmatrix} 0 & -\frac{1-d}{L} \\ \frac{1-d}{C} & -\frac{1}{RC} \end{bmatrix}, \mathbf{B} = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, \mathbf{C} = [0 \ 1], \mathbf{D} = 0, \tag{3}$$

where L is the inductance of the boost converter, C is the output capacitance, R is the load resistance, and d is the duty cycle.

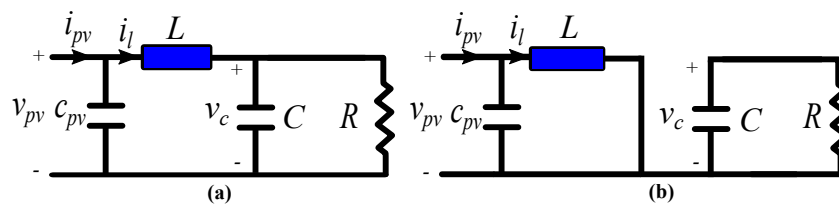


Figure 1. Equivalent circuit of the boost converter when: (a) switch is OFF, and (b) switch is ON.

3. The PV Model-Based MPPT Techniques

In this section, the main MPPT techniques will be discussed and investigated. In this matter, the primary classification of the PV model-based MPPT algorithm is given as methods based on curve fitting procedures and techniques of mathematical models (equations) according to the PV characteristics. In the following, a detailed analysis of these methods is to be addressed.

3.1. Determination of the MPP Location (Characteristics-Based)

- The constant voltage method

It is considered the simplest method for MPPT, where the system is operated at a constant voltage value. This value is specified according to the data-sheet of the utilized PV module, where the voltage at standard test conditions (STC) (1000 W/m² and 25 °C) is selected to be the optimal value. Only, a voltage measurement is needed in this algorithm, where the controller is maintaining the sensed voltage at the chosen reference voltage [52]. The constant voltage method does not account for the variation of the MPP with the temperature. However, it gives a satisfactory performance under radiation change, where the MPP voltage variation range is restricted to a narrow range with respect to the radiation variation [53]. Furthermore, this method is not operating at the MPP [54].

- The open-circuit voltage method

The open-circuit voltage technique depends on finding a relation between the open-circuit voltage and the MPP voltage at different atmospheric conditions. It is reported that the required relation is linear, and hence, it can be written as [55]:

$$v_{mpp} = k_{oc} v_{oc}, \tag{4}$$

where v_{mpp} is the MPP voltage at different operating conditions of temperature and radiation, k_{oc} is the proportionality constant, and v_{oc} is the measured open-circuit voltage. The value of the constant in Equation (4) depends on the used PV module. However, a range of 0.71–0.78 is assigned for the available PV modules in the market [56]. The implementation of the open-circuit voltage method needs to isolate the PV source from the converter circuit to enable the open-circuit voltage measurement. Therefore, additional components are in need of utilization in the PV system to accomplish such measurement. Similarly, the voltage measurement is required in this scheme and the goal of the controller is to keep the sensed voltage in the vicinity of the calculated MPP voltage.

- The short-circuit current method

This method is very similar to the open-circuit method. However, the current is used here as a control parameter, where the relation between the MPP current at different atmospheric conditions and the short-circuit current can be given as [57]:

$$i_{mpp} = k_{sc} i_{sc}, \quad (5)$$

where k_{sc} is a constant to be adjusted. According to the literature, the known range for this constant is 0.78–0.92 [56]. Normally, to implement such a method, an electronic switch is utilized across the PV module and a momentary short circuit is applied to permit the current measurement. The short circuit operation or the open circuit one as in the previous method is normally applied every several seconds. Therefore, even if the adjustable factor is properly calibrated, the system is not operating at the MPP, where the atmospheric conditions are continuously changing between the moments of measurements [20,58]. However, and due to the inclusion of atmospheric condition variation in these methods, it is expected to have a better performance in comparison with the constant voltage technique.

- The pilot cell technique

The open circuit and short circuit methods suffer from power losses during the measurements of the voltage or current [20]. Therefore, the pilot cell is used in these methods to realize the measurements without the need for load disconnection. To be specific, this method is normally used with PV arrays (large systems), where the real system is kept without change. However, a pilot cell is used in the same location to accomplish the open-circuit voltage or short-circuit current measurement. Then, the measured value is used in the original system. However, the pilot cell should have identical characteristics to the PV array. This implies inaccuracies in addition to the cost of the calibration of pilot cell/array configuration [56].

- On-line fractional open-circuit voltage algorithm

The aforementioned drawbacks of the open circuit method are avoided in this technique, where the open-circuit voltage is estimated online based on the measurements and the model of the PV source. In this matter, the estimation is given by [59,60]:

$$v_{ocn} = v_{oc} + nN_s v_t \left[\ln\left(\frac{i_{phn}}{i_{ph}}\right) \right] + k_v(T - T_n), \quad (6)$$

where v_{ocn} is the open-circuit voltage at certain atmospheric condition, i_{phn} is the photovoltaic current at the same condition, k_v is the open-circuit voltage temperature coefficient, v_t is the thermal voltage, T_n is the nominal temperature, and the values v_{oc} and i_{ph} are calculated at STC. Furthermore, the estimation process of the photovoltaic current (i_{ph}) is obtained from Equation (1). Therefore, to implement this approach, the voltage, current, and temperature values should be known (measured). Still, the tuning of the proportionality constant is a drawback of this method.

- The temperature method

In this technique, the dependency of the MPP voltage on the temperature is considered. The MPP voltage variation is linear when the temperature changes, which gives [39,61]:

$$v_{mpp} = v_{mppn} + k_v(T - T_n), \quad (7)$$

where v_{mppn} is the MPP voltage at STC. It is quite obvious that the radiation variation in this method is neglected. Thus, it is more suitable for the one or two module configuration (low power). To implement this method, the voltage measurement alongside the temperature is required.

- MPP voltage determination

The objective of this method is to get a formulation for the location of the MPP voltages. In [62], a similar formulation like the open-circuit voltage is also used for the MPP voltage location, which is expressed as:

$$v_{mpp} = \frac{v_{mppn}}{1 + \delta \ln\left(\frac{G_n}{G}\right)} + k_v(T - T_n), \quad (8)$$

where δ is a constant (0.05) and is adjusted by minimizing the squared error using experimental data for the open-circuit voltage at different radiation conditions. A similar formula is used in [63], in which the temperature is neglected. However, the temperature impact was taken into consideration in [64]. It is quite obvious that the implementation of this method requires the knowledge of the atmospheric conditions (radiation and temperature) in addition to the voltage measurement. To decrease the cost of the sensing circuitry, the radiation or the temperature can be estimated [65]. However, the efficiency of the PV system is then more dependent on the estimation accuracy. A new formulation is suggested for the MPP voltage in [66] as:

$$v_{mpp} = \left(\frac{-c}{a + ab}\right)^{\frac{1}{b}}, \quad (9)$$

where a and b are temperature-dependent parameters, and c is calculated as:

$$c = i_{pv} - a v_{pv}^b. \quad (10)$$

To implement this method, the voltage, current, and temperature are required.

In [19], a methodology that considers an analogy between the open-circuit point and the MPP, where the MPP voltage at different radiation and temperature conditions can be estimated from:

$$v_{mpp} = v_{mppn} \left[1 + k \log\left(\frac{G}{G_n}\right)\right] + k_v(T - T_n), \quad (11)$$

where $k = nN_s v_t / v_{mppn}$.

- MPP current determination

In this technique, the location of the MPP currents is determined. This method is inspired by the fractional short-circuit current. However, no disconnection of the load is required, where the MPP currents can be computed according to:

$$i_{mpp} = i_{mppn} \frac{G}{G_n}. \quad (12)$$

The previous formula is well-known for the photovoltaic current representation as [44,45,67]:

$$i_{ph} = [i_{phn} + k_i(T - T_n)] \frac{G}{G_n}. \quad (13)$$

However, as the photovoltaic current is proportional to the MPP current, a similar formulation for the MPP current location can be used. It is worth mentioning that the effect of the temperature on the MPP currents is minor. Therefore, it is not included

in Equation (12). In the same context, one should keep in mind that the effect of the temperature on the MPP voltage is significant.

3.2. Curve Fitting Technique

In this approach, the location of the MPP voltages is obtained based on a curve-fitting tool. In [68], a linear approximation for the location of the MPP, where one line is used to represent the high radiation levels, and the second line represents the lower radiation values. Furthermore, a cubic polynomial is provided to further adjust the location of the MPP in [69].

The linear approximation is given by:

$$\begin{aligned} v_{mpph} &= k_h i_{pv} + v_{oh}, \\ v_{mssl} &= k_l i_{pv} + v_{ol}, \end{aligned} \quad (14)$$

where v_{mpph} and v_{mssl} represent the location of the MPP voltages at high and low radiation conditions, respectively. k_h and k_l are the slopes of the lines. Furthermore, v_{oh} and v_{ol} are the offset voltages at the same conditions.

The cubic formula is given by:

$$v_{mpp} = a i_{pv}^3 + b i_{pv}^2 + c i_{pv} + v_o, \quad (15)$$

where a , b , c , and v_o are the parameters of the polynomial.

Similarly, the PV power can be represented in terms of the PV voltage as [57,70]:

$$p_{pv} = k_1 v_{pv}^3 + k_2 v_{pv}^2 + k_3 v_{pv} + k_4, \quad (16)$$

where k_1 , k_2 , k_3 , and k_4 are the coefficients of the polynomial resulting from the sampled PV voltage and power. Differentiating the previous formula gives:

$$\frac{dp_{pv}}{dv_{pv}} = 3k_1 v_{pv}^2 + 2k_2 v_{pv} + k_3. \quad (17)$$

At MPP,

$$\frac{dp_{pv}}{dv_{pv}} = 0. \quad (18)$$

Therefore, the voltage at MPP can be located as:

$$v_{mpp} = \frac{-k_2 \pm \sqrt{k_2^2 - 3k_1 k_3}}{3k_1}. \quad (19)$$

In this methodology, the constants (k_1 , k_2 , k_3 , and k_4) are repeatedly sampled in a span of a few milliseconds [57].

4. Experimental Results and Discussion

4.1. Test Bench Description

The studied PV system is composed of a PV module, boost converter, and resistive load. The power circuit is built using HIL (RT Box CE), and the control action is obtained from a dSPACE MicroLabBox. The real-time controller sends the switching signals to the digital inputs of the HIL system, where the measurements are fed back to the analog inputs of the dSPACE controller. The configuration of the experimental test bench of the PV system is shown in Figure 2. Furthermore, the parameters of the power circuit are given in Table 1. It is worth mentioning that the PV module KC200GT is used as a source of power. The characteristics of this module are previously presented [2]. The HIL system provides several merits for implementation, where difficult situations and various scenarios can be easily achieved. Furthermore, step and fast changes in atmospheric conditions are hard to realize in reality. This gives a better evaluation of the PV system's performance.

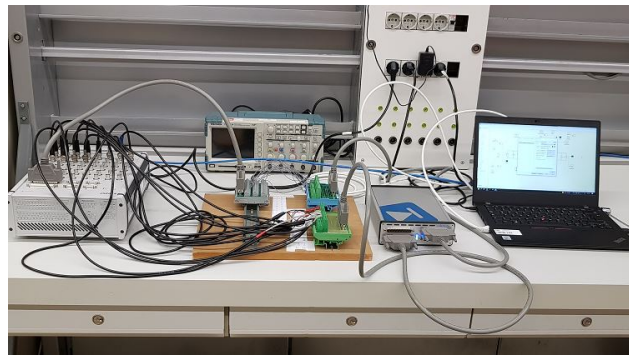


Figure 2. The experimental set-up of the PV system.

Table 1. The parameters of the power circuit of the PV system.

Parameter	Value
Boost inductance (L)	5 mH
Output capacitor (C)	200 μ F
Load resistance (R)	10 Ω
Switching frequency	5 kHz
Sampling time (T_s)	100 μ s

4.2. Performance of MPPT

The experimental results are divided into three cases, where step change of radiation, step change of temperature, and dynamic profile for the radiation are used to evaluate the performance of the PV system. The methods considered for experimental assessment are the constant voltage method and temperature method [61]. Furthermore, from the category of MPP voltage determination, the voltage-based technique (V1) [62] and voltage-based method (V2) [19] are selected. Moreover, from the category of MPP current determination, the current-based approach (Equation (12)) is chosen. The curve fitting approach is also included [69]. The instantaneous and average efficiencies are used to evaluate the performance of the MPPT techniques. They can be expressed according to [18]:

$$\eta_{pv} = \frac{P_{mppt}(t)}{P_r(t)} \times 100, \quad (20)$$

where P_{mppt} is the produced maximum power using a certain MPPT technique and P_r is the reference power (from the data-sheet).

$$\eta_{pv,avg} = \frac{\int P_{mppt}(t)dt}{\int P_r(t)dt} \times 100. \quad (21)$$

Firstly, in Figure 3, the radiation is changed from 600 W/m² to 1000 W/m² and the temperature is kept constant at 25 °C, where the PV power, voltage, current, and instantaneous efficiency are shown, respectively. All studied methods succeed to follow the fast change in the radiation. The constant voltage method behavior is very similar to the temperature method, where the reference voltage from both techniques is equal as the temperature is maintained constant in this test. The voltage-based approach (V1) performance is a little bit lower when compared with the constant voltage and temperature schemes due to the inaccuracies in the voltage reference estimation process, especially when the operating point differs from the STC. This is further investigated in Figure 4, where the steady-state waveform of the PV power is shown. One can clearly observe that the constant voltage and the temperature methods have a very similar ripple pattern. The voltage-based method (V2) and the current approach are also similar. However, their behavior is enhanced in comparison with the constant voltage and temperature techniques. The ripple of the voltage algorithm (V1) is higher in comparison with other schemes. The curve fitting

approach behaves similarly to the constant voltage and temperature methods, as clarified in Figure 4. Table 2 summarizes the average PV efficiencies of all studied methods, where the voltage-based (V1) technique has the lowest average efficiency among all studied methods at the step change of radiation. Following, the constant voltage method and temperature one give enhanced efficiencies in comparison with the voltage method (V1). Furthermore, the average efficiency values for these methods are approximately equal. The voltage (V2), curve fitting, and current methods' efficiencies are the highest. Additionally, the execution times are given in the same table (Table 2). The constant voltage method, temperature, and current-based algorithm have almost identical calculation times. However, voltage-based technique (V1), voltage-based method (V2), and curve fitting require higher execution times due to the computational load of the reference voltage.

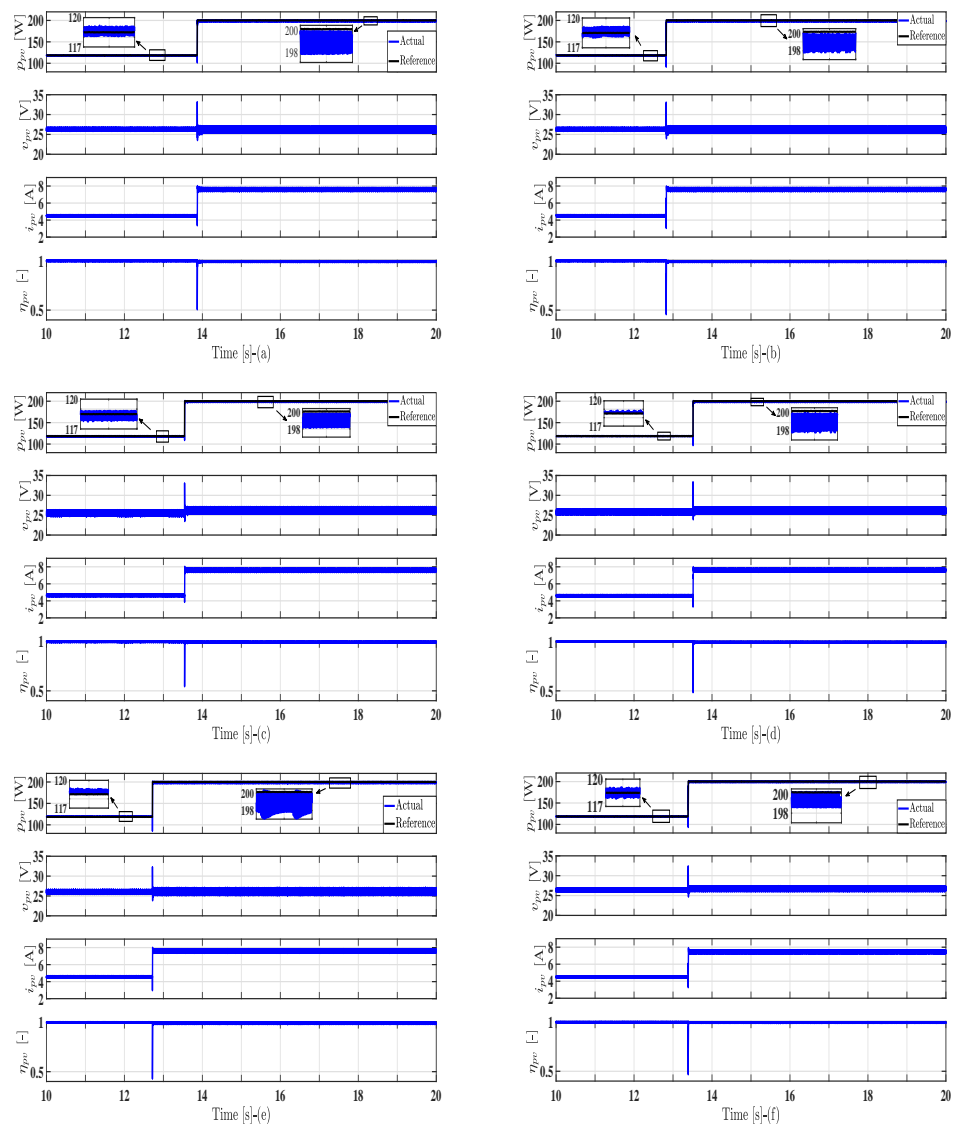


Figure 3. The performance of model-based MPPT methods at a step change of radiation. (a) Constant voltage method, (b) temperature method, (c) voltage-based method (V1), (d) voltage-based technique (V2), (e) current-based algorithm, (f) curve fitting approach.

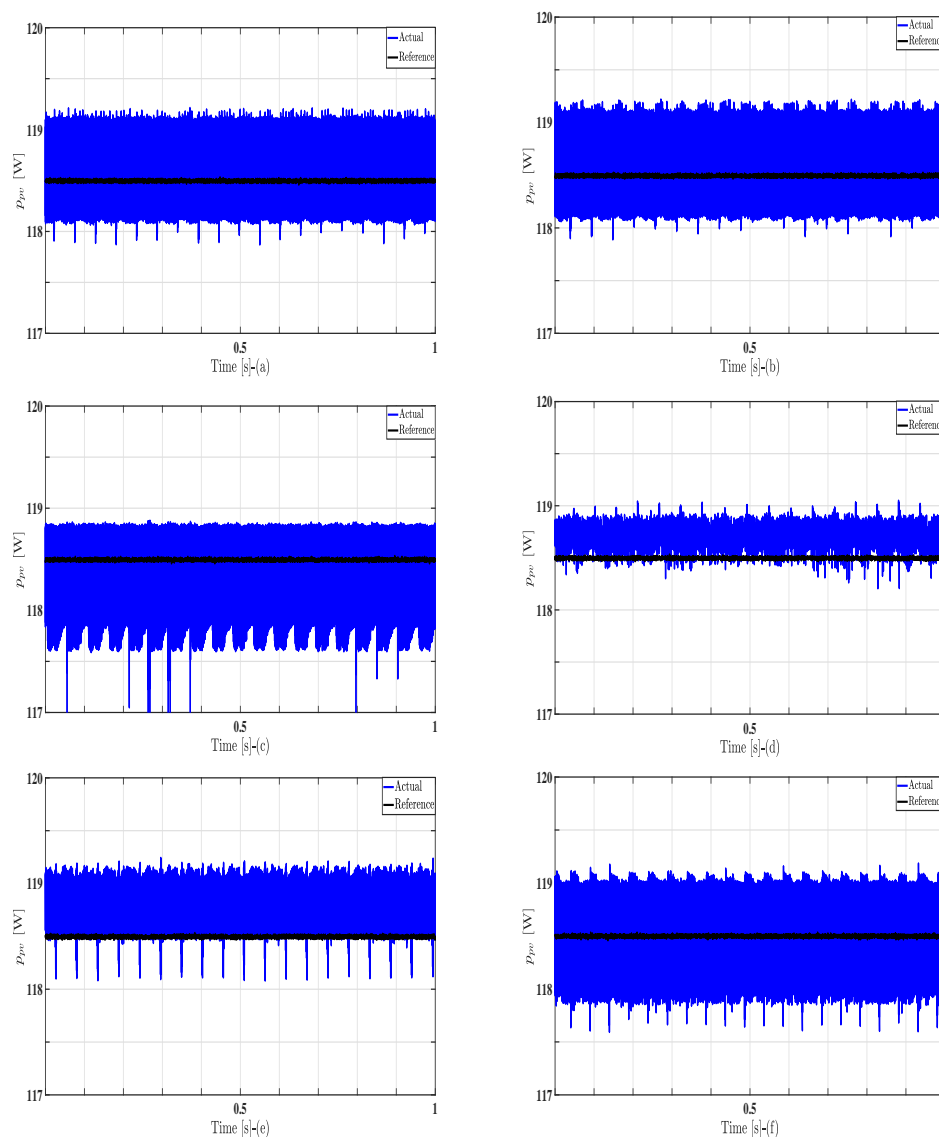


Figure 4. The steady-state performance of model-based MPPT methods at 600 W/m^2 radiation. (a) Constant voltage method, (b) temperature method, (c) voltage-based method (V1), (d) voltage-based technique (V2), (e) current-based algorithm, (f) curve fitting approach.

Table 2. Average efficiencies and execution times of the model-based MPPT techniques at step change of radiation.

Method	$\eta_{pv,avg}$ (%)	Execution Time (μs)
Constant voltage method	99.70	6.82
Temperature method	99.68	6.81
Voltage-based technique (V1)	99.60	7.46
Voltage-based method (V2)	99.73	7.45
Current-based algorithm	99.74	6.83
Curve fitting approach	99.75	7.53

In Figure 5, the same former methods are studied at step change of temperature from $50 \text{ }^\circ\text{C}$ to $25 \text{ }^\circ\text{C}$, where the radiation is kept constant at 1000 W/m^2 . In this regard, the performance of the constant voltage method is poor due to the negligence of the temperature effect in this method. This is clearly obvious in the case of the high-temperature condition in the first interval of Figure 5. However, the performance of the temperature method, voltage one (V1), the voltage-based estimation (V2), and curve fitting is very similar, where the

reference voltage estimation is identical in the four methods in terms of temperature impact. The current-based algorithm performance is a little bit affected when the temperature changes. The summary of average efficiencies at the step change of temperature is given in Table 3. It is clear that the constant voltage method efficiency is poor under temperature variation. Therefore, it is expected for a wide voltage range of operation, where several modules are connected in series, the performance of this method may cause significant power loss and lead to operation near the open-circuit point.

Table 3. Average efficiencies of the model-based MPPT techniques at step changes of temperature.

Method	$\eta_{pv,avg}$ (%)
Constant voltage method	87.65
Temperature method	99.43
Voltage-based technique (V1)	99.44
Voltage-based method (V2)	99.43
Current-based algorithm	99.37
Curve fitting approach	99.46

In the last case, a dynamic profile for the radiation is used to evaluate the efficiencies of the model-based techniques. The ramp profile is recommended by the European efficiency test (EN50530) [71] to assess the performance of the PV system. Therefore, a similar profile, which is the triangular waveform is used to emulate the dynamic change of the radiation. This is a built-in function in the utilized HIL box, which simplifies the implementation of the former test.

Figure 6 shows the performance of the MPPT methods at dynamic variations of radiation. At the first glance, the response of all methods is very similar. Therefore, a zoomed part from this figure is further investigated in Figure 7 to show the dynamics of power, voltage, and current.

Moreover, to understand the differences among the various model-based schemes, the power-voltage curves for all studied methods are examined in Figure 8. The significance of these curves is to highlight the variation band of the voltage versus power. If this band is narrow, this means that the change of voltage is restricted to the maximum power region. Furthermore, if the former band is wide, this indicates that there is a deviation from the maximum power location. For the constant voltage method, temperature method, and voltage estimation technique (V2), the power-voltage behavior is very similar, where the band of voltage variation is approximately 1 V at low-power values, and 2 V in case of high-power levels. The voltage-based estimation method (V1) has the widest voltage range in comparison with other model-based schemes, where, at some operating points, the band is 3 V. The current-based procedure and the curve fitting method have the lowest margin of voltage variation among all studied methods.

As previously mentioned, the voltage-based scheme (V1) has the worst behavior (when considering radiation variation) among the studied model-based techniques due to the inaccurate reference voltage estimation. This is clearly obvious in the power-voltage response shown in Figure 8 and further investigated in Table 4 in terms of the average efficiency at dynamic weather conditions. The average efficiency of the constant voltage, temperature method, and voltage reference computation (V2) is approximately equal. The efficiency of the voltage-based method (V1) is the lowest among all methods. The behavior of the current-based and curve fitting approaches is outstanding, where the average efficiency is the highest.

Briefly, the model-based MPPT techniques give a high tracking efficiency. However, both temperature and radiation should be taken into consideration. At variations of radiation, the efficiency of all studied techniques is comparable. When the temperature changes, the constant voltage method gives poor tracking efficiency. However, the efficiency values of other model-based methods are close. Minor derivations in the efficiency are mainly related to the accuracy of the reference estimation (voltage or current). In this matter,

the voltage-based method (V2), current-based algorithm, and curve fitting approach present the best estimation values for the reference. Therefore, they have improved performance in comparison with other estimation techniques (model-based).

Table 4. Average efficiencies of the model-based MPPT techniques at ramp variations of radiation.

Method	$\eta_{pv,avg}$ (%)
Constant voltage method	99.93
Temperature method	99.93
Voltage-based technique (V1)	99.71
Voltage-based method (V2)	99.94
Current-based algorithm	99.99
Curve fitting approach	99.99

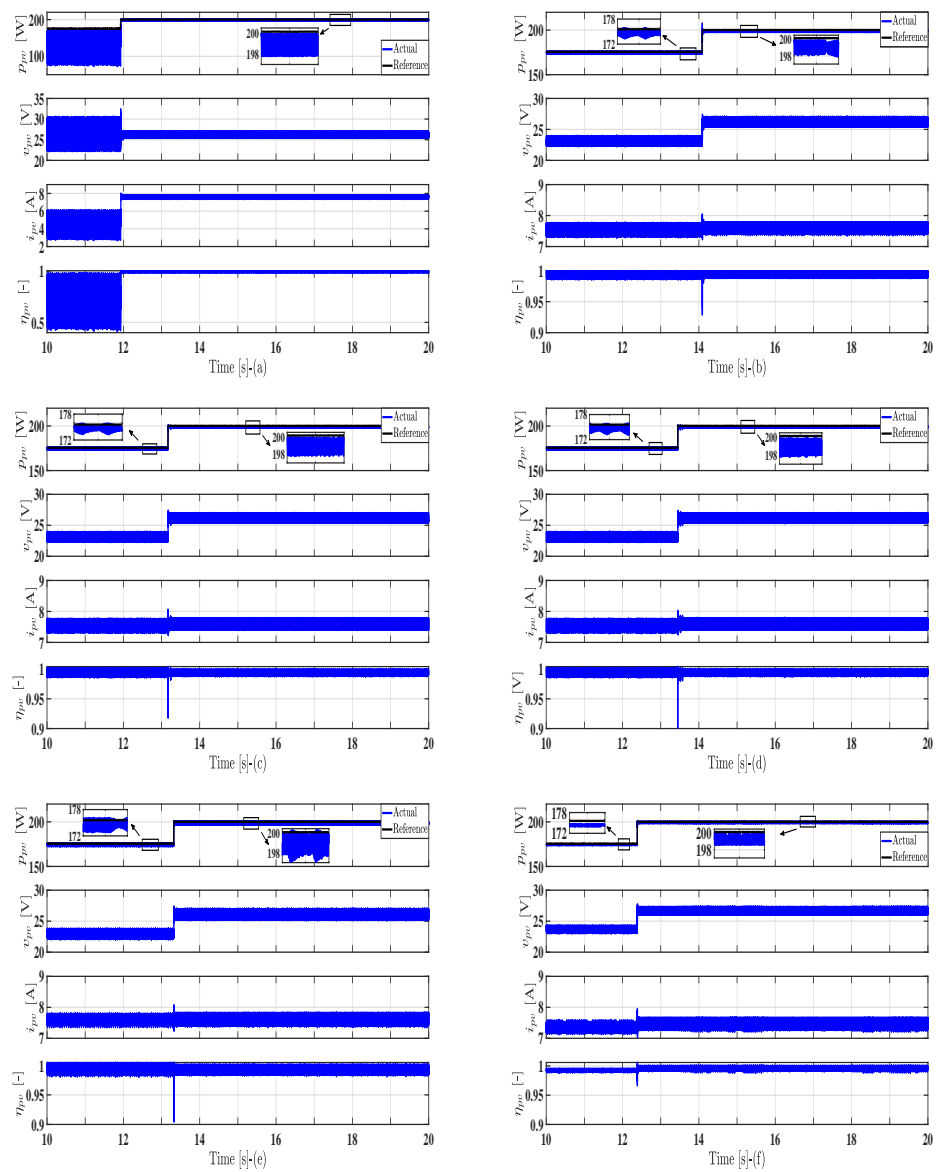


Figure 5. The performance of model-based MPPT methods at step changes of temperature. (a) Constant voltage method, (b) temperature method, (c) voltage-based method (V1), (d) voltage-based technique (V2), (e) current-based algorithm, (f) curve fitting approach.

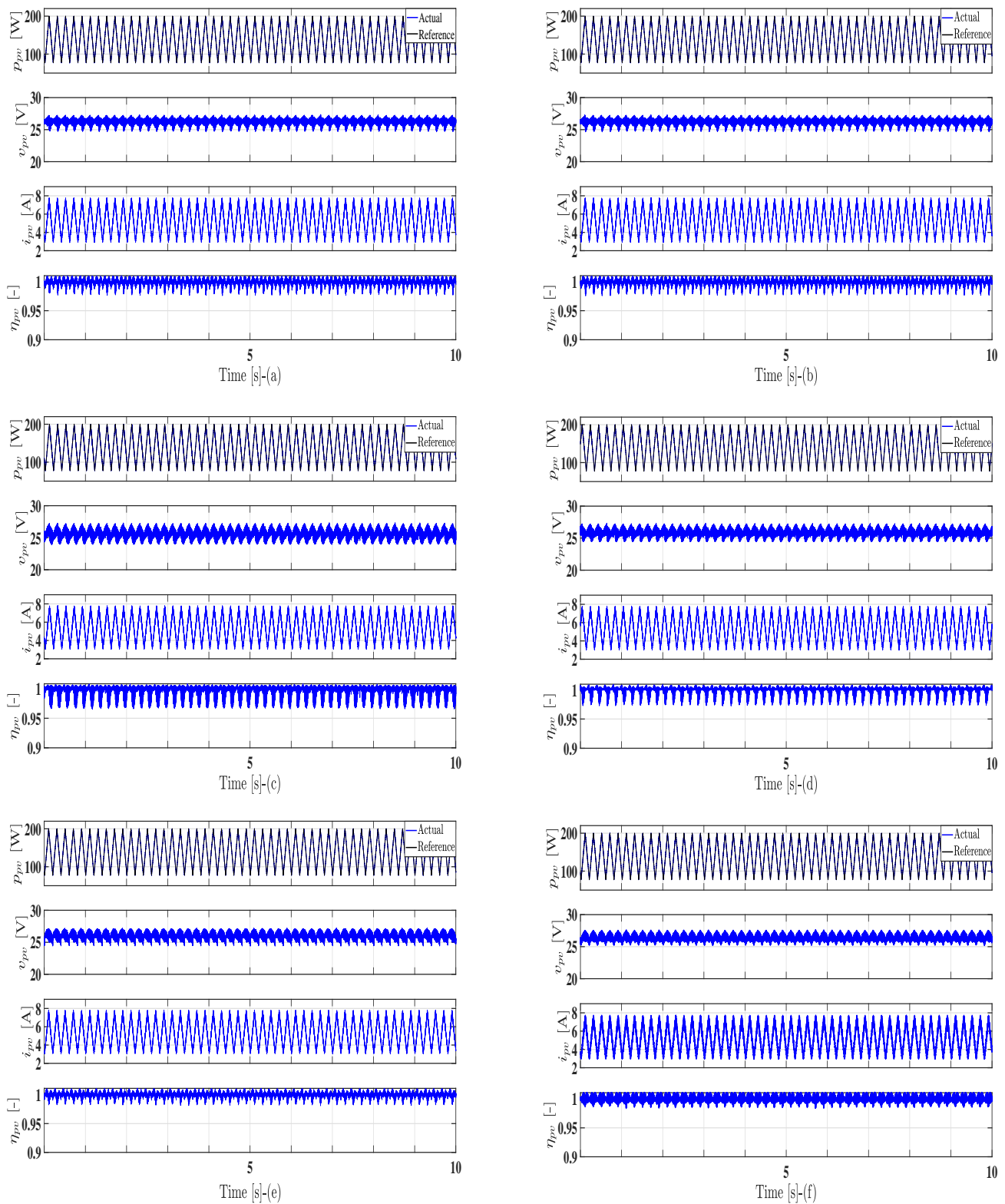


Figure 6. The performance of model-based MPPT methods at dynamic variations of radiation. (a) Constant voltage method, (b) temperature method, (c) voltage-based method (V1), (d) voltage-based technique (V2), (e) current-based algorithm, (f) curve fitting approach.

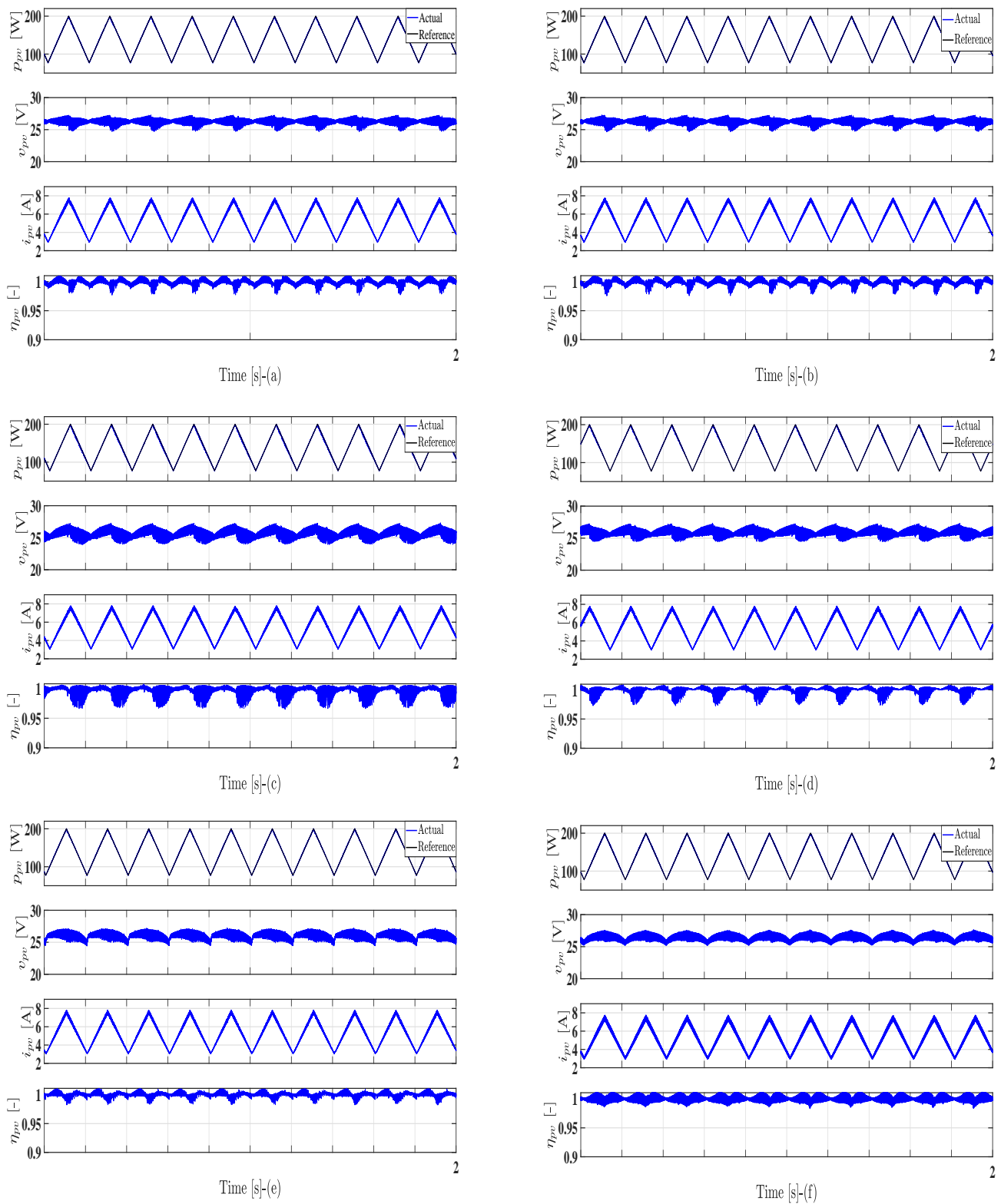


Figure 7. The performance of model-based MPPT methods at dynamic variations of radiation (zoomed view). (a) Constant voltage method, (b) temperature method, (c) voltage-based method (V1), (d) voltage-based technique (V2), (e) current-based algorithm, (f) curve fitting approach.

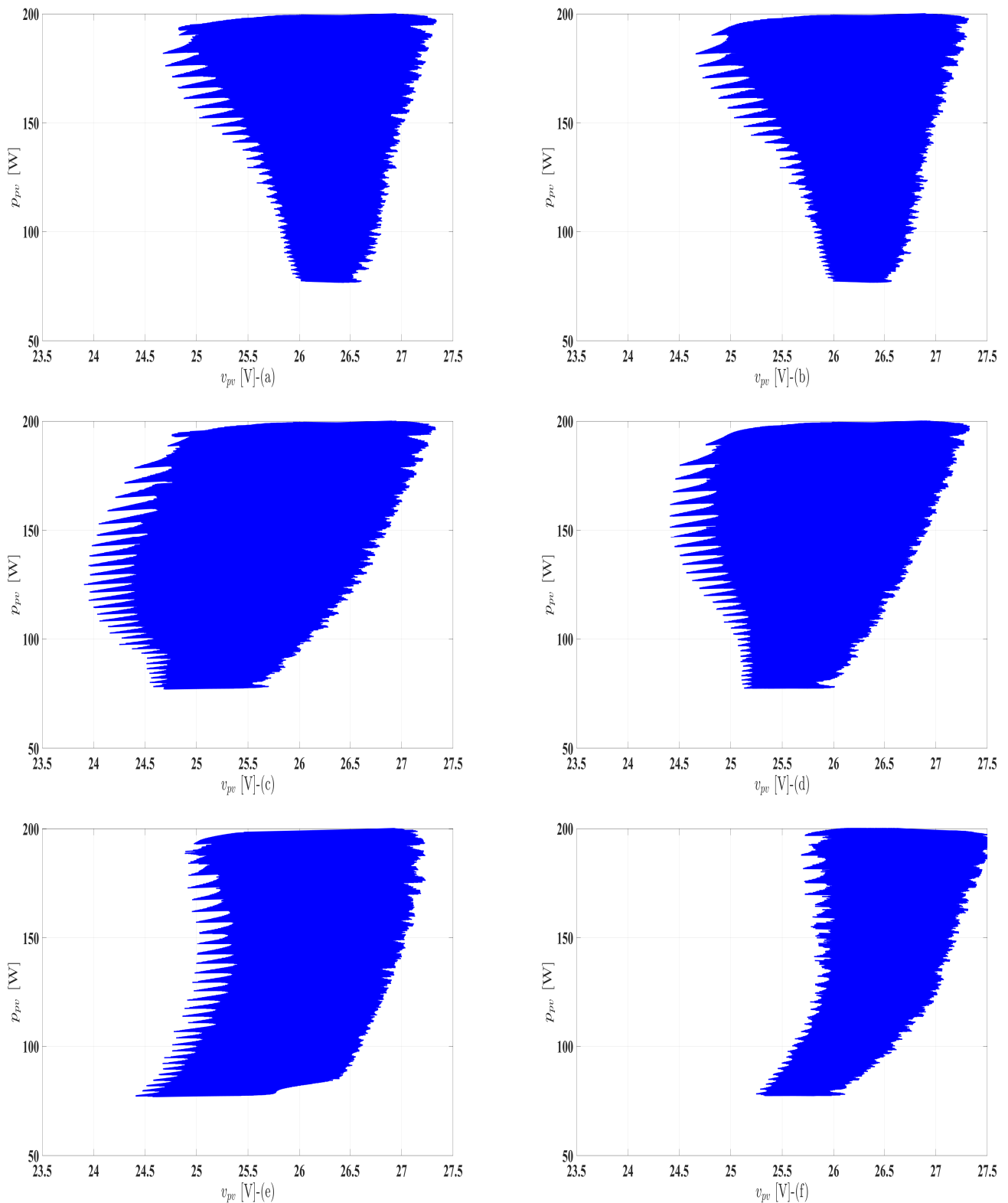


Figure 8. The power-voltage response of model-based MPPT methods at dynamic variation of radiation. (a) Constant voltage method, (b) temperature method, (c) voltage-based method (V1), (d) voltage-based technique (V2), (e) current-based algorithm, (f) curve fitting approach.

Another remark that should be mentioned concerning the studied model-based MPPT techniques is the inclusion of atmospheric conditions. In the constant voltage method and current-based approach, the temperature effect is neglected. Therefore, their efficiency

has been affected. The temperature method also does not include the radiation variation. Thus, it has a reduced efficiency value under radiation change. Other schemes, including voltage-based methods (V1&V2) and curve fitting, consider both temperature and radiation variation. Consequently, they have improved performance. However, the voltage-based algorithm (V1) suffers from inaccuracies in the reference voltage estimation. Nevertheless, these methods are expected to give a significant improvement in case of higher power levels provided that both temperature and radiation impacts are considered in the estimation.

5. Discussion

- The model-based MPPT is known for high tracking speed and efficiency due to the restrictions imposed on the voltage or current reference computation. Therefore, when compared with searching algorithms, the model-based schemes give an enhanced performance.
- In the same context, the searching-based schemes such as the P&O method may have a divergent performance in the case of fast-changing atmospheric conditions, where the algorithm is confused due to perturbation. However, this issue is solved in the PV model-based methods because of the inclusion of atmospheric conditions.
- The current-based algorithm has a fast-tracking response at temperature variations as the current change due to temperature is small (see Figure 5, where the current change due to temperature is approximately negligible), in contrast to the voltage methods, where the voltage variation due to temperature is linear. Furthermore, and in view of the radiation changes, the current-based methods are slower when compared to the voltage-based ones, where the voltage is restricted to a narrow range in case of radiation change. However, the current change is proportional to the radiation.
- The model-based approaches need an accurate model for an improved efficiency, where the effect of the temperature and radiation should be included in the developed method. In this regard, the constant voltage method gives a poor performance at various temperature conditions. This is mainly because of the negligence of temperature effect in this scheme.
- A major drawback of the model-based methods is the utilization of temperature and radiation sensors. Therefore, the application of these methods is not popular as the case of searching-based schemes, which use voltage and current sensors. However, the temperature sensor can be eliminated if the module temperature is controlled using an appropriate cooling system. Thus, the model-based schemes can work properly in floating systems (PV floating systems constructed in seas, oceans, or lakes). This not only reduces the required sensors but also increases the efficiency, where the cooling contributes to such an increase.
- Further on, estimation techniques of the temperature and radiation could contribute to the development of the model-based approaches.
- The constant voltage method is the simplest among all studied methods, where only one voltage sensor is required for implementation. The temperature method comes in the second place, where an additional temperature sensor is needed for execution. The current-based algorithm uses a current sensor and a radiation one. Furthermore, the voltage-based methods (V1 and V2) utilize voltage, temperature, and radiation sensors. The curve fitting approach uses voltage, current, and temperature sensors.
- The efficiency of all studied methods, except for the constant voltage technique, is very high. Therefore, in terms of cost, the temperature method is advised for implementation. However, for high power applications, and due to the negligence of the radiation effect, the voltage-based estimation (V2) procedure is recommended, especially at such a power level, that the sensor cost is not an issue.
- The development of more sophisticated model-based MPPT techniques is recommended to improve the system's efficiency.
- Sensor reduction is also advised, where one or two measurements can be estimated. In this regard, robust online estimation is required. Optimization techniques can benefit

in this matter. However, this may come at the cost of high computational power and even more complex implementation.

To this end, Table 5 briefly compares all studied MPPT methods in terms of implementation cost, the performance at temperature variation, required sensors, and calculation burden. The constant voltage method presents a poor performance at temperature variation. However, its implementation cost is low. The voltage-based approaches (V1 & V2) provide an improved performance due to the inclusion of both radiation and temperature effects. However, the sensor requirements of these techniques are higher, which increases the cost of the system. Temperature and current-based methods give a reasonable compromise between the cost and performance. The computation effort of the curve fitting, voltage-based (V1), and voltage-based (V2) is high in comparison to other techniques. In this regard, and based on the system's requirement, one can choose the suitable MPPT method.

Table 5. Brief comparison among the model-based MPPT methods.

Method	Implementation Cost	Behavior at Temperature Variation	Sensors	Calculation Burden
Constant voltage method	Very low	Poor	V	Low
Temperature method	Low	Excellent	V, T	Low
Voltage-based technique (V1)	High	Excellent	V, T, G	High
Voltage-based method (V2)	High	Excellent	V, T, G	High
Current-based algorithm	Medium	Very Good	I, G	Low
Curve fitting approach	High	Excellent	V, I, T	High

6. Conclusions

A comparative study among the main model-based MPPT techniques has been conducted in this work. The model-based MPPT methods depend mainly on the characteristics of the PV source, where a determination of the MPP location is sought in these approaches. Therefore, the performance of the model-based schemes is dependent on the accuracy of the utilized model. In this regard, different model-based MPPT techniques are considered for evaluation using experimental HIL set-up (at different atmospheric conditions of radiation and temperature) in this research. As a main remark, the model-based methods are known for high tracking efficiency provided that both temperature and radiation effects are taken into consideration. Furthermore, the simplified implementation is a major feature of these techniques, where no searching algorithms are required. The average efficiency of all studied methods is more than 99% at different operating conditions except for the constant voltage method when the temperature changes. The temperature method and the voltage-based estimation (V2) have an improved efficiency when compared with the voltage-based method (V1). The performance of the current approach is superior when compared to other schemes. However, at temperature variation, its behavior is slightly reduced. The curve fitting approach performance is also accurate. However, several constants are in need to be calculated. From a cost perspective, the temperature method is recommended for low-power applications and the voltage-based technique (V2) is advised for high-power systems. In conclusion, more sophisticated model-based MPPT are in need to be explored for efficiency enhancement. Furthermore, radiation and temperature estimation techniques are encouraged to be applied within the MPPT area to further simplify the implementation procedure and decrease the cost. The continuous development of real-time controllers (microprocessors) will simplify the implementation of hybrid techniques (optimization and traditional techniques) for efficiency improvement.

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