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A novel maximum power point tracking technique based on fuzzy logic for photovoltaic systems

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ABSTRACT

Maximum power point tracking (MPPT) techniques are considered a crucial part in photovoltaic system design to maximise the output power of a photovoltaic array. Whilst several techniques have been designed, Perturb and Observe (P&O) is widely used for MPPT due to its low cost and simple implementation. Fuzzy logic (FL) is another common technique that achieves vastly improved performance for MPPT technique in terms of response speed and low fluctuation about the maximum power point. However, major issues of the conventional FL-MPPT are a drift problem associated with changing irradiance and complex implementation when compared with the P&O-MPPT. In this paper, a novel MPPT technique based on FL control and P&O algorithm is presented. The proposed method incorporates the advantages of the P&O-MPPT to account for slow and fast changes in solar irradiance and the reduced processing time for the FL-MPPT to address complex engineering problems when the membership functions are few. To evaluate the performance, the P&O-MPPT, FL-MPPT and the proposed method are simulated by a MATLAB-SIMULINK model for a grid-connected PV system. The EN 50530 standard test is used to calculate the efficiency of the proposed method under varying weather conditions. The simulation results demonstrate that the proposed technique accurately tracks the maximum power point and avoids the drift problem, whilst achieving efficiencies of greater than 99.6%.

Introduction

In recent years, the global demand for energy has increased dramatically due to population growth. In addition, the phenomenon of global warming has been intensified owing to the CO_2 emissions from fossil fuels. To solve this complex challenge, many studies have called for the use of renewable energies to face the issue of lack of energy in future years and to minimise the side effects of burning fossil fuels. Hence, developing renewable energies has been become a worthy research topic in the last decade. A solar photovoltaic (PV) systems, wind turbines, hydropower, biomass and geothermal power are the major renewable energy resources. The solar PV arrays are considered one of the most attractive renewable energy resources due to their provision of sustainable, clean and safe energy [1]. However, the efficiency of a PV system is low, because the output power of a PV array is dependent on irradiance and temperature, i.e. weather conditions, which can result in a loss of energy of up to 25% [2]. The most effective way to improve the efficiency of a PV system is to employ a maximum power point tracking MPPT

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technique with it, as shown in Fig. 1, thereby achieving maximum power production under varying weather conditions. Basically, The MPPT technique is an electronic system, which feeds an appropriate duty cycle (D) to a power conversion system for the output and/or input of the PV module to achieve continuous maximum power production. In general, there are several issues that are key when aiming to design the best MPPT technique for a PV system, including cost, efficiency, lost energy, and type of implementation [3,4]. Taking an account of these, many types of MPPT methods have been developed for PV systems, which can be divided into two types: classical methods, such as Perturbation and Observation (P&O) [5], Incremental Conductance (IC) [6], and Fractional Open Circuit Voltage [7]; and artificial intelligent techniques, for instance, Neural-fuzzy ANFIS [8], Fuzzy Logic (FL) [9], genetic algorithms (GAs) [10], particle swam optimism (PSO) [11], sliding mode [12] and Neural Networks (NNs) [13]. The P&O-MPPT is a popular method for PV-MPPT owing to its low cost and simple implementation [14]. However, it poses many challenges, such as lower converging speed, high oscillation around a maximum power point MPP, and a drift problem associated with rapidly changing irradiance [5,15]. Several modifications have been introduced based on a Power (P)–Voltage (V) curve [16–20], but they are considered as insufficient solutions for addressing all of these problems. Consequently, artificial intelligent techniques based on MPPT have been proposed to solve the significant problems of the classical MPPT methods [21]. In addition, these techniques do not need accurate parameters or complex mathematics when managing the system [22,23]. In particular, the FL-MPPT technique is one of the most powerful controllers for a PV system due to its high converging speed and low fluctuation around the MPP [24,25]. Moreover, it does not require training data, thus resulting in its working for various types of PV module with the same MPPT design. However, the main disadvantages are the aforementioned drift problem associated with changing irradiance and complex implementation when compared with the classical MPPT methods [26,27].

Several types of modification have been proposed to address those issues. Among them, the authors in Ref. [28] used the PSO algorithm to adjust the duty cycle of the boost convertor in the right direction for conventional FL-MPPT when the input solar irradiance changes rapidly. In Ref. [29], the authors designed a gain controller based on the FL approach for online adapting of the step size of conventional FL-MPPT. In Ref. [30], the author developed a novel FL-MPPT

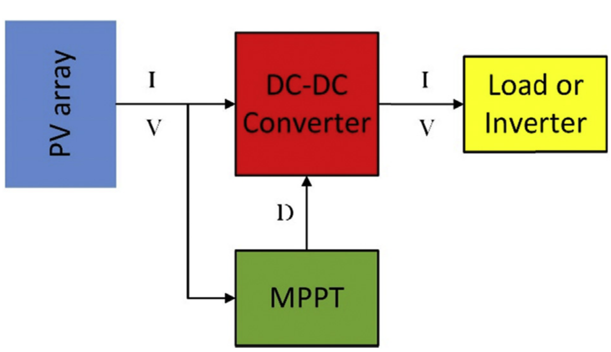

Fig. 1 – Diagram of PV system based MPPT.

based on a hill climbing algorithm for a stand-alone PV system. In Refs. [31,32], the researchers presented an improved maximum power point tracking technique using the Fuzzy-IC algorithm for a PV array and fuel cells. The authors in Ref. [33] improved the conventional FL-MPPT method by adding fuzzy cognitive networks. Whilst these proposals reduce the oscillations around the MPP and avoid the drift problem during changing irradiance, their implementation becomes more complex due to an additional step control unit. Hence, the authors in Ref. [34] used a GA algorithm to optimise the designed membership functions of the conventional FL-MPPT controller for which the fuzzy base had already been created. Similarity, the author in Ref. [35] presented maximum power point tracking based on an asymmetrical fuzzy functions process to minimise the longer processing time of conventional FL-MPPT. With the same idea, the researcher of [36] presented maximum power point tracking by modelling the fuzzy logic algorithm using an M5P model tree. In Ref. [37], the authors used a Hopfield NN to tune the designed membership functions of FL-MPPT automatically, instead of adopting the trial-and-error approach. Similarity, the scholars in Ref. [38] designed improved maximum power point tracking based on an indirect fuzzy for PV systems. The results in Refs. [34–38] report that the optimised fuzzy controller achieved improved performances, fast responses with less oscillations as well as avoiding the drift problem. However, the implementation of all these methods is more complex than for the classical MPPT techniques.

In this paper, a novel FL-MPPT technique based on a modified P&O algorithm is designed. The proposed design takes into account two key issues. First, whilst the conventional P&O-MPPT is a suitable method for the PV system under a slow change of irradiance, it faces significant challenges under a fast one. The second issue, is that the complex engineering problems of a fuzzy system become diminished when the designed membership functions are few. The fuzzy rules of the proposed method are obtained from a modified P&O-MPPT algorithm. The proposed technique accurately tracks the maximum power point and avoids the drift problem. Moreover, our simplified FL-MPPT method, when applied to a grid-connected PV system, achieved efficiencies greater than 99.6% under the EN 50530 standard test. The rest of this paper is organised as follows. Section Modelling of solar PV covers the basic modelling of a solar PV cell, whilst Sections Power conversion system and MPPT technique explain the workings of a power conversion system and MPPT controller, respectively. Section Conventional P&O-MPPT and Conventional FL-MPPT discuss the P&O and FL –MPPT, respectively. In Section Proposed method, the proposed method is presented, whilst the simulated results are provided and discussed in Section Simulation results. The EN 50530 standard test results for comparative analyses are provided in Section The EN 50530 standard test of MPPT efficiency, with Section Conclusion containing the conclusion.

Modelling of solar PV

Solar cell is an electrical device that converts the light energy into electricity by the photovoltaic effect. In ideal PV cell, parallel and series resistances are not present but in practical case they are included due to leakage current and ohmic resistances as shown in Fig. 2. While major contributor to the shunt resistance R_{sh} is that a p–n junction of PV diode is non-optimal, the series resistance R_s are the bulk resistance of semiconductor material and interconnections. When PV cell is supplied solar irradiance the output current from the solar PV cell can be found using Kirchhoff's law, as shown in Eq. (1):

$$I_{PV} = I_L - I_d - I_{sh} \quad (1)$$

where I_L is the light generated current and given as in Eq. (2):

$$I_L = G\{I_{SC}[1 + a(T - T_{STC})]\} \quad (2)$$

where, G is the solar irradiance, I_{SC} is the PV short circuit current, a is the temperature coefficient of short circuit current, T is the temperature operation, T_{STC} is the temperature operation for the PV cell under standard test conditions (STC). And I_d is the diode current and given as Eq. (3):

$$I_d = I_0\left\{\exp\left(\frac{qV_d}{nkT}\right) - 1\right\} \quad (3)$$

where I_o is the reverse saturation current of the diode, and V_d is the Voltage across diode, q is the electric charge (1.69×10^{-19} C), k is the Boltzmann's constant (1.38×10^{-23} J/K), and n is the diode idealist factor. A general equation that describes the I–V characteristic curve of the PV cell is shown in Eq. (4) [1]:

$$I_{PV} = I_L - I_0\left[\exp\left(\frac{q(V_{PV} + I\,R_S)}{nkT}\right) - 1\right] - \left[\frac{V_{PV} + I\,R_S}{R_{sh}}\right] \quad (4)$$

where I_{PV} is the PV output current, and V_{pv} is the PV output voltage of PV cell.

Solar cells are connected in parallel and series to obtain desired current and voltage respectively for the solar panel, and then the solar panels are connected in series and/or parallel to give different configurations of PV array. As shown in Fig. 3, there is unique point on the P–V curve of the PV array, which is known as the maximum power point (MPP) and this depends on solar irradiance and temperature [3,39]. The voltage operation of PV array also depends upon the impedance of the load. When PV array is connected to the load it drops to a new operating point. To address those issues, power conversion system and MPPT technique are connected between PV array and the load or invertor, as shown in Fig. 1.

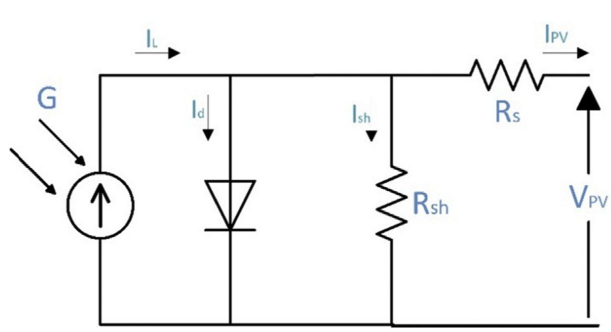

Fig. 2 – Equivalent circuit of PV solar cell.

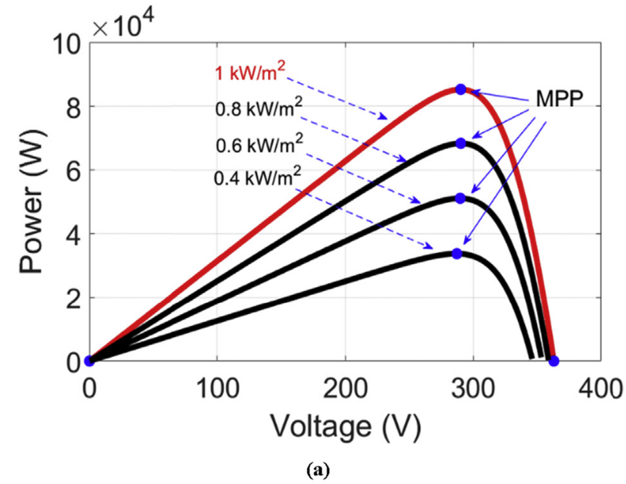

Fig. 3 – P–V curve of a PV array under: a) various values of irradiance at a temperature of 25 °C; b) various values of temperature at an irradiance of 1000 W/m^{2}.

Power conversion system

To improve the stability, reliability and quality of the output of PV system generation, a power conversion system is employed [40]. There are two types for PV power conversion system; single stage and double stage. Although the single stage-power conversion system is lower in cost due to its fewer part count, it suffers from several drawbacks such as hot-spots during partial shading conditions of the PV array, increased probability of leakage current through the parasitic capacitance between the PV array and the ground system, and reduced safety. Those issues occurred in grid-connected PV system due to a large change in DC voltage of PV array. Therefore, the first stage is used to boost the MPP voltage and track the maximum power, and the second stage converts this DC power into high quality AC power. In first stage, a DC-DC boost converter is widely used for the PV generated system due to its high efficiency and easily adapted MPPT controller. It is used to provide and regulate an appropriate the output voltage that has level which is considerably more than the input voltage. As shown in Fig. 4, the heart of the DC-DC boost converter is a transistor, which regulates the amplified processing by a controller. The MOSFET transistor is usually used for this kind of converter. The voltage gain of the circuit is given as in Eq. (5) [41]:

$$G_n = \frac{V_o}{V_i} = \frac{1}{(1-D)} \quad (5)$$

where V_o is the output voltage, V_i is the input voltage, and D is the duty cycle of DC-DC boost converter, which is converted to a control signal by a gate driver circuit. The principle work of this converter divides into two states, first, when the MOSFET is switched ON; the current flows through an inductor (L) in a reverse direction and the inductor stores the energy by generating a magnetic field, while the output capacitor (C2) transfers its energy to the load or invertor. In state two, when the transistor is switched OFF, the energy stored and main source will be in series, which leads to a higher output voltage. In the grid-connected PV system, the DC-DC boost converter plays a crucial role in maintaining a constant DC voltage system for a DC-AC inverter.

MPPT technique

As shown in Fig. 3 and mentioned previously, there is a unique point on the P–V curve of a PV array called the maximum power point (MPP), with its location shifting according to weather conditions. To track the MPP continuously, the MPPT technique is employed with the power conversion system. In general, the MPPT is an electronic system, the principle of which is to feed the appropriate duty cycle, D, to the power conversion system for the output of the PV array in the form of the current and voltage and/or the inputs of solar irradiance and temperature. This duty cycle is converted to signal by a gate driver circuit for adjusting the power conversion system operation. The optimal duty cycle depends on the location of the operational point on the P–V curve. In the last few years, many MPPT methods have been presented, each having its advantages and disadvantages. There are several issues that need to be taken into account when seeking the best technique, including cost, efficiency, lost energy, and type of implementation. Some examples found in the literature are P&O, IC, Fractional Open Circuit Voltage Feedback Voltage or Current, FL, ANFIS, GA, PSO, sliding mode and NN-MPPT.

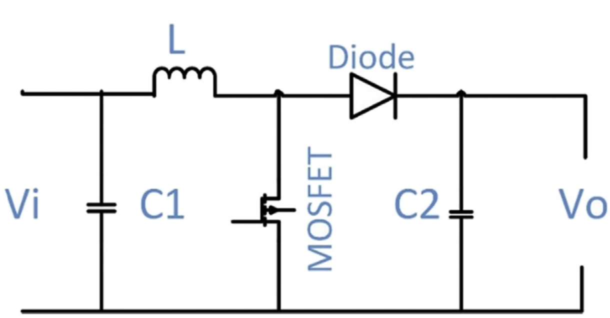

Fig. 4 – Circuit diagram of a DC-DC boost converter.

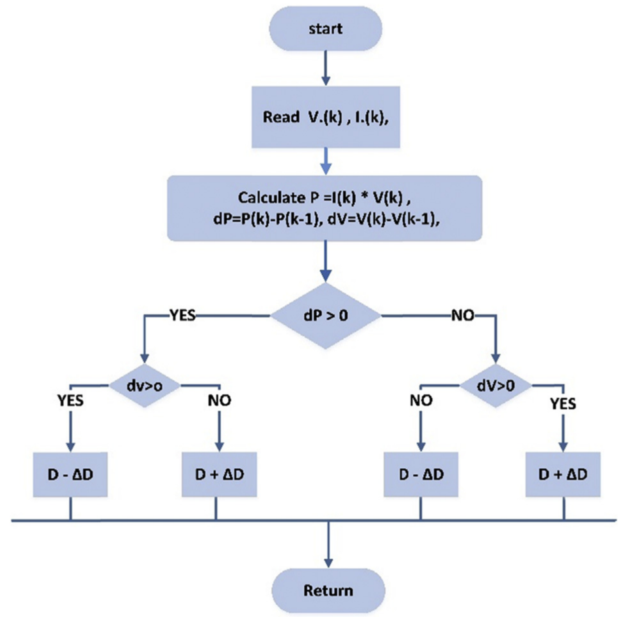

Fig. 5 – Flowchart of a conventional P&O method.

Conventional P&O-MPPT

The P&O algorithm is widely used for PV-MPPT due to its low cost and simple implementation. As shown in Fig. 5, the principle work of this algorithm calculating the PV power by using the sensed values of the voltage and current of the PV module. These are then compared with the previous power and voltage, with the direction of the algorithm being adjusted accordingly and the duty cycle of the boost converter being adjusted as in Eq. (6):

$$D_{k+1} = D_k \pm \Delta D \quad (6)$$

where D_k and D_{k+1} are the previous and next perturbation of duty cycle respectively, and ΔD is the constant width of the step size. Basically, if the tendency of change in PV voltage and PV power increase regarding to an increase in the duty cycle, the control system moves in the same direction; otherwise the operating point moves in the opposite direction. The process is continued until it reaches to the MPP and then it oscillates around the optimal MPP. The probabilities of the direction P&O-MPPT algorithm are explained in Table 1. In general, there are three main issues facing its operation: a long convergence time, high oscillation around the MPP and a drift problem associated with irradiance changing rapidly. These issues detailed as follows. Clearly, a large ΔD leads to a faster steady state and large oscillations after reaching the MPP.

Table 1 – The probabilities of the direction P&O algorithm.

ΔP	ΔV	Direction of perturbation
+	+	+
+	−	−
−	+	−
−	−	+

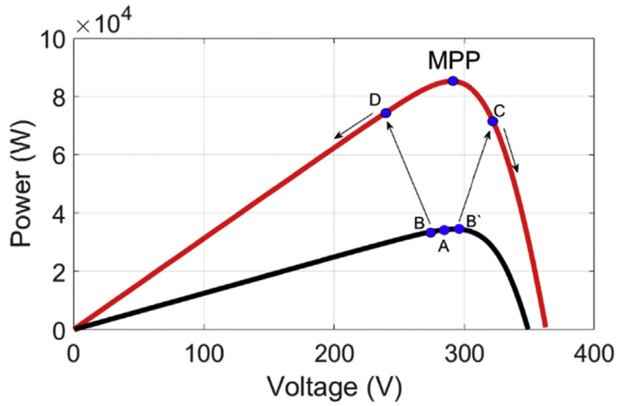

Fig. 6 – P-V curve for a rapid irradiance change from A (low point) to D or C (high point), thus illustrating the drift problem in the P&O-MPPT algorithm.

Conversely, a small ΔD results in a slower steady state and smooth fluctuations. Owing to this, the size of ΔD is considered a crucial issue that needs controlling in the system.

Another drawback is loss of the right direction of the algorithm when the weather conditions change rapidly. This phenomenon can happen, as shown in Fig. 6, when point A (low point), which represents the MPP at a low irradiance level, is oscillating between B and B′ and then moves to point C or D (high point) due to rapid increase in the irradiance. As a result, the right direction of algorithm moves far away from the new MPP, regarding to the principle properties direction of the conventional P&O-MPPT algorithm, as illustrated in Table 1. In other words, this phenomenon is happened in case of the increasing irradiance only [42]. Hence, the efficiency of the P&O-MPPT will fall regarding to above issues. To solve these drawbacks, variable step size and an adaptive P&O-MPPT algorithm have been developed. However, they are considered insufficient solutions to address all of these issues. Consequently, artificial intelligence techniques based on PV-MPPT have been proposed to overcome the limitations of the classical P&O-MPPT method.

Conventional FL-MPPT

Nowadays, FL control based on an MPPT technique has become a popular method for PV systems [26]. The structure of FL control includes three stages: fuzzification, fuzzy rules and defuzzification. A block diagram of this technique is shown in Fig. 7. In first stage, the input variables are converted into linguistic variables based on many defined membership functions. In next stage, these linguistics variables get manipulated, according to rules based on the "if–then" concept that are guided by the desired behaviour of the system. In the last stage, the FL control converts the linguistic variables into numerical variables using the output of membership functions. In general, the quantity of membership functions is considered an important aspect of the design as it determines the speed and accuracy of the FL system [9].

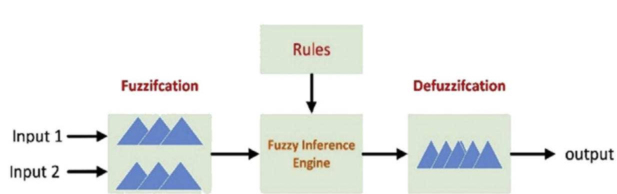

Fig. 7 – A general diagram of the fuzzy logic system.

Table 2 – The fuzzy rules that are used in the conventional FL-MPPT.

Δe	e				
	NB	NS	ZZ	PS	PB
NB	ZZ	ZZ	NB	NB	NB
NS	ZZ	ZZ	NS	NS	NS
ZZ	NS	ZZ	ZZ	ZZ	PS
PS	PS	PS	PS	ZZ	ZZ
PB	PB	PB	PB	ZZ	ZZ

If the system has more membership functions. The implementation problem becomes over complex, resulting in an accurate system but with an excessive processing time. In contrast, if the system has few membership functions, then it is simple and whilst there is a faster processing system time and there is a high acceptable diversity of outcomes.

The conventional FL- MPPT has two inputs and one output, as shown in Eqs. (7) and (8) [43]:

$$e(k) = \frac{\Delta P}{\Delta V} = \frac{P_{(k)} - P_{(k-1)}}{V_{(k)} - V_{(k-1)}} \quad (7)$$

$$\Delta e = e_{(k)} - e_{(k-1)} \quad (8)$$

where *e(k)* is the change of slop P–V curve, and *Δe* is the change in its value of slop P–V curve. The output is the change of duty cycle *ΔD*, which adjusts the performance of DC-DC converter as through Eq. (9) [22]:

$$\Delta D = \frac{\sum_i^n W_i\, C_i}{\sum_i^n W_i} \quad (9)$$

where W_i is the minimum number of membership functions of the ith rule and C_i is the centre value of the output membership functions. The work of the conventional FL-MPPT is to examine the first input, if this value is greater than zero the incremental change of the duty cycle increases until the MPP is reached, whereas if it is less than zero then the opposite occurs until the optimal value is reached. The second input is then used to reduce the oscillation in the duty cycle effectively. The quantity of membership functions of the conventional FL-MPPT method is divided into five values: negative big (NB), negative small (NS), Z, Zero (ZZ), positive small (PS), and positive big (PB). For example, if the value of the error is NB and changing error also negative big PB, the predefined rules assign the next variable duty cycle as ZZ, with process continuing until the optimal MPP is reached. All the rules of the FL-MPPT algorithm are provided in Table 2. In general, FL-MPPT is considered one of the most efficient controllers for a PV system due to its smooth fluctuation, and high accuracy in reaching the MPP. In addition, as mentioned earlier, it does not require training data and thus works on different types of

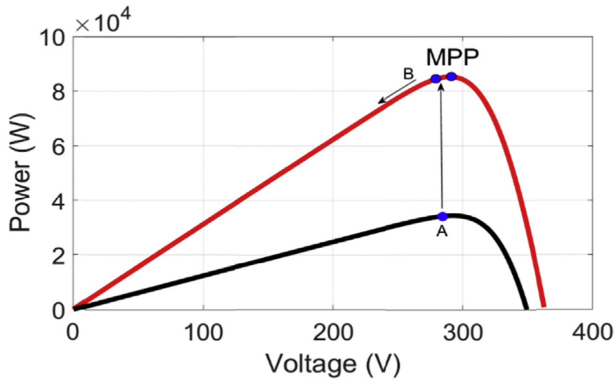

Fig. 8 – P-V curve for a rapid irradiance change from A (low point) to B (high point), thus illustrating the drift problem in the FL-MPPT algorithm.

PV module the same MPPT design. In other words, it needs a comprehensive study about the PV system operation to design an accurate controller. Moreover, implementation of this method is complex compared with the classical MPPT methods. The main challenge of this method is the drift phenomenon happens when weather conditions change, which Fig. 8 explains. If Point **A** (low point), which represents the MPP at a low solar irradiance level is moving to **B** (high point) due to a rapid increase in solar irradiance, the right direction of the fuzzy tracker is moving far away from the new MPP, according to the rule base of the conventional FL-MPPT algorithm, as show in Table 2. To solve this issue. Many modifications have been proposed, such as an adaptive and optimised membership function of the conventional FL-MPPT algorithm. However, in this case the implementation becomes much more complex.

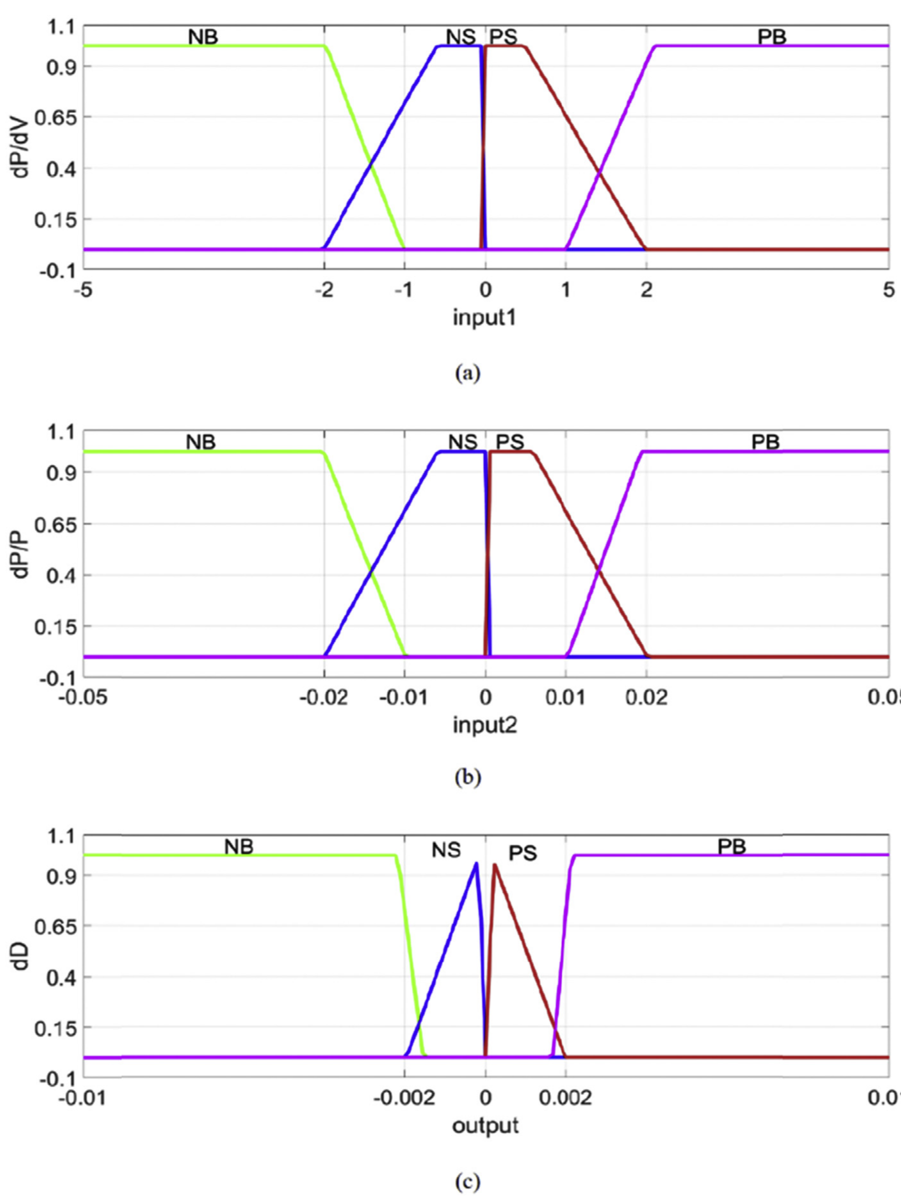

Fig. 9 – The designed membership functions of the proposal: (a) input1 $\Delta P/\Delta V$; (b) input2 $\Delta P/P$; and (c) output ΔD.

Proposed method

The proposed method is designed to incorporate the advantages of the FL-MPPT and P&O-MPPT algorithms, whilst eliminating their drawbacks. Many studies provided evidence that the P&O algorithm is a suitable method for a PV-MPPT system when solar irradiance changes slowly from 1 to 10 $W/m^2/s$. However, this method is flawed when the changing irradiance is quicker than this. Therefore, the irradiance is classified into two types: fast change and slow change, as shown by Eqs. (10) and (11) [44].

$$\Delta G > 10\ W/m^2/s \quad \textit{fast change} \tag{10}$$

$$\Delta G < 10\ W/m^2/s \quad \textit{slow change} \tag{11}$$

where ΔG is the historical change in solar irradiance.

$$\text{The standard test condition (STC) of } G = 1000\ W/m^2/s \tag{12}$$

Substituting Eq. (12) into Eqs. (10) and (11), the following is obtained:

$$\frac{\Delta G}{G} > 0.01 \quad \textit{fast change} \tag{13}$$

$$\frac{\Delta G}{G} < 0.01 \quad \textit{slow change} \tag{14}$$

As proved in Ref. [45], the normalised change in PV Power is equal to the normalised change in the solar irradiance, as shown in Eq. (15):

$$\frac{\Delta P}{P} = \frac{\Delta G}{G} \tag{15}$$

Substituting Eq. (15) into Eqs. (13) and (14), then:

$$\frac{\Delta P}{P} > 0.01 \quad \textit{fast change} \tag{16}$$

$$\frac{\Delta P}{P} < 0.01 \quad \textit{slow change} \tag{17}$$

where ΔP is the historical change in PV power and P is the previous iteration for PV power. If the value of P is changed due to a solar irradiance change, the value of ΔP also changes in the same direction. Consequently, the value of $\Delta P/P$ is almost constant during varying weather conditions. This value is used in the fuzzy rules to detect the drift problem early. Defining the input and output of membership functions is considered an important step in the fuzzy logic design [46] and those for the proposed system are selected as follows:

$$\frac{\Delta P}{\Delta V} = \frac{P_{(k)} - P_{(k-1)}}{V_{(k)} - V_{(k-1)}} \tag{18}$$

$$\frac{\Delta P}{P} = \frac{P_{(k)} - P_{(k-1)}}{P_{(k-1)}} \tag{19}$$

where the first represents the historical change in PV power relative to the historical change in PV voltage, whilst the second pertains to the historical change in PV power relative to the previous iteration for it and the output of proposed fuzzy system is:

Table 3 – The fuzzy rules that are used in the proposed method.

ΔP/P	ΔP/ΔV			
	NB	NS	PS	PB
NB	NB	NS	PS	PB
NS	NB	NS	PS	PB
PS	NB	NS	PS	PB
PB	PB	PS	NS	NB

$$D_k = D_{k-1} + \Delta D \tag{20}$$

where D_{k-1} and D_k are the previous and next iteration for the duty cycle respectively, and ΔD its incremental increase, which is the output of the fuzzy controller. The principle work of this proposal is to examine the first input. If this value is greater than zero the incremental change of the duty cycle increases until the MPP is reached, whilst if it is less than zero the opposite occurs also until the optimal value is reached. While the second input is then used to address the drift problem. The variable inputs and output are divided into four fuzzy subsets: positive big (PB), positive small (PS), negative big (NB), and negative small (NS), as show in Fig. 9. The variable second input ($\Delta P/P$) is adjusted according to Eqs. (16) and (17). The fuzzy rules of the proposed system are based on the P&O-MPPT algorithm, with there being a total of 16. If the value of ($\Delta P/\Delta V$) is NB and ($\Delta P/P$) is also NB, then so too is the duty cycle is NB. The process is continued until the optimal MPP is reached and then it oscillates around the optimal MPP. To avoid the drift problem associated with positive fast change in solar irradiance, the fuzzy rules are changed in a reverse direction when ($\Delta P/P$) > 0.01, which is equal to the PB in the second input. All the fuzzy rules of the proposed MPPT method are provided in Table 3.

The output of proposed system is the variable duty cycle ΔD, which is added to the previous iteration for the duty cycle, as show in Eq. (20). As a result, the step size of the duty cycle is large when the operational point is far from the MPP, and it automatically becomes tiny, when the operational point closes in on it. Consequently, the proposed system increases the speed of MPPT tracking when the weather conditions change rapidly. In addition, it reduces the oscillation around the MPP for steady-state conditions. Moreover, what is proposed is more accurate for addressing the new MPP when the irradiance changes owing to the adaptive rules of the fuzzy system according to weather conditions. Furthermore, the proposed system provides less complex implementation, minimum processing time and more delivery compared with the conventional FL-MPPT, because of its lesser number of fuzzy rules.

Simulation results

To test the performance of the proposed method, a MATLAB-SIMULINK model for the PV system has been developed. The PV system used in this simulation consists of a PV array, DC–DC boost converter with MPPT controller and a grid, as

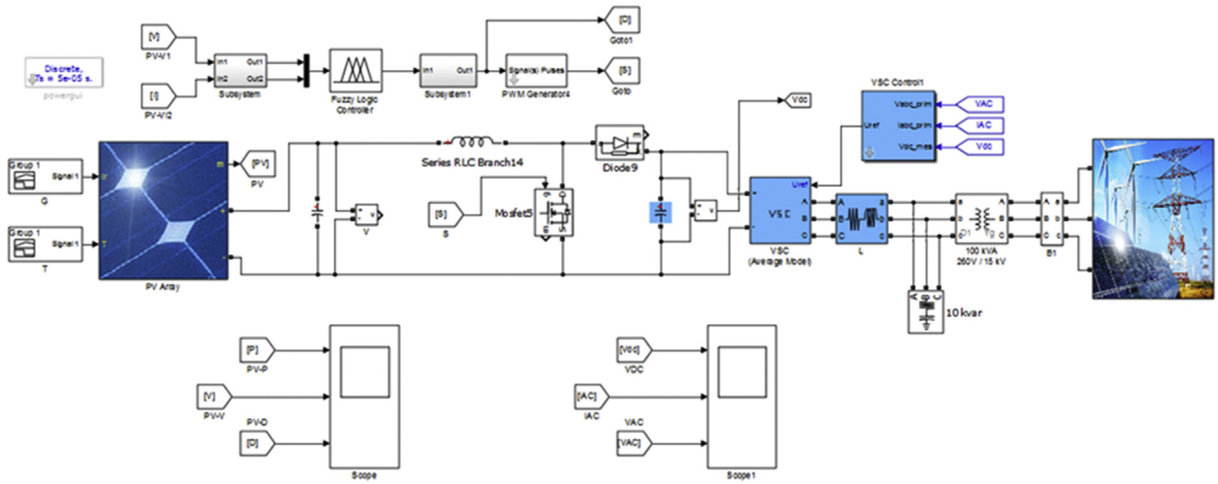

Fig. 10 – Simulink model of a grid-connected PV system based on the proposed method.

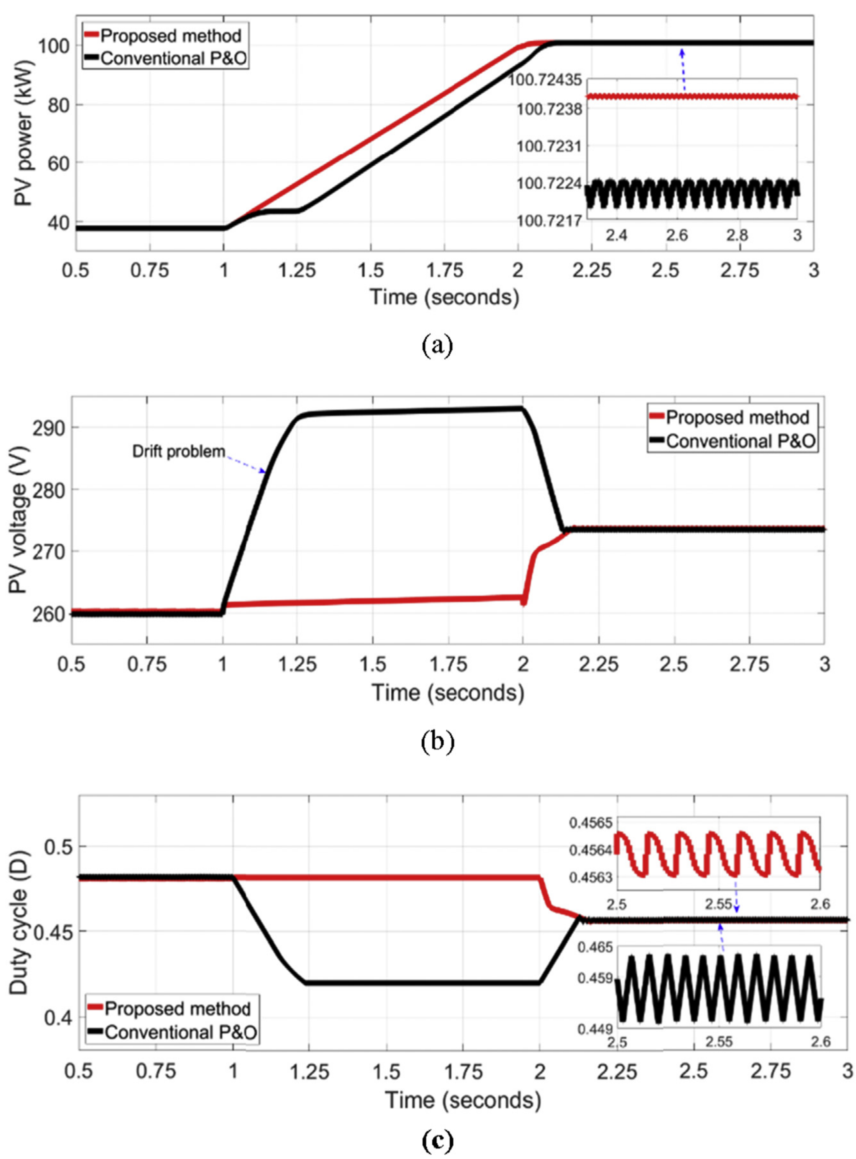

Fig. 11 – PV module system for the proposed method versus conventional P&O under rapidly changing weather conditions: (a) power, (b) voltage, and (c) duty cycle.

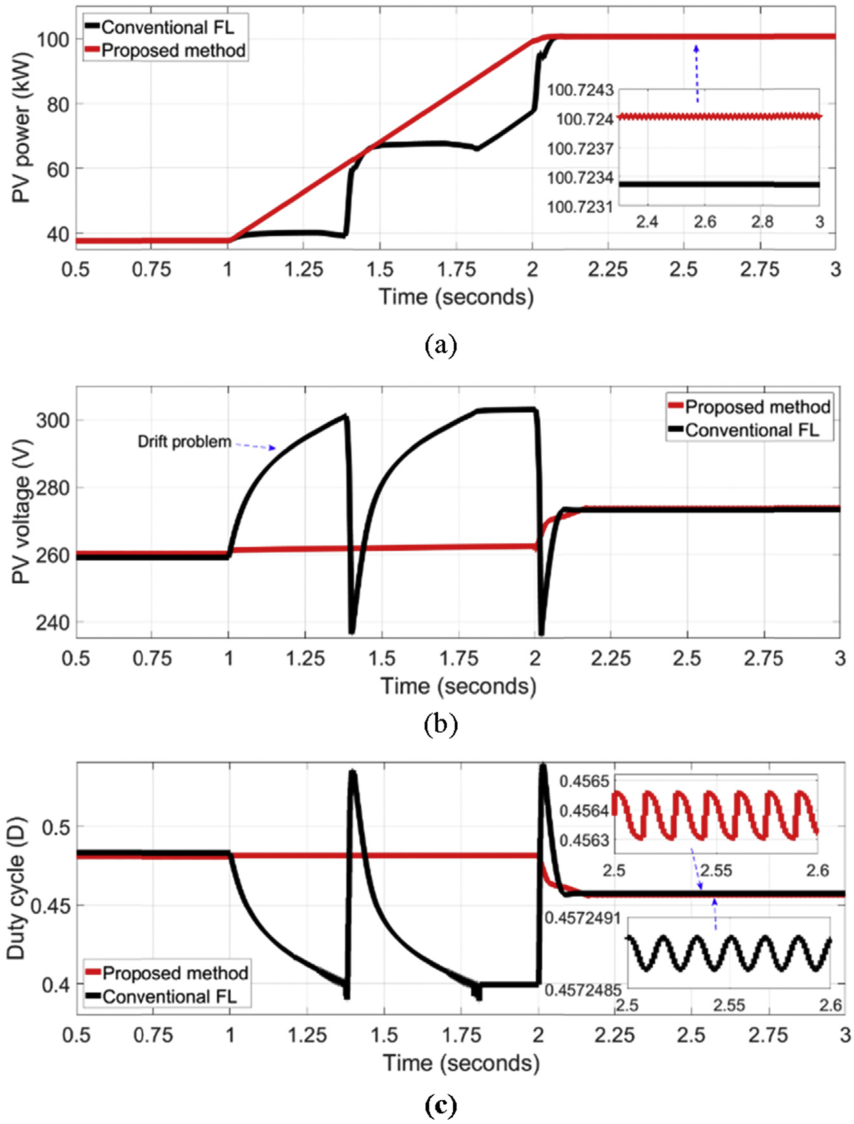

Fig. 12 – PV module system for the proposed method versus conventional FL under rapidly changing weather conditions: (a) power, (b) voltage, and (c) duty cycle.

show in Fig. 10. The parameters of PV array are 320 V open-circuit voltage and 390 A short-circuit current under the STC. The simulation was divided into two scenarios. First, the proposed method and conventional P&O were simulated. The input solar irradiance was rapidly increased from 400 to 1000 W/m^2 at 1 to 2 s, and the temperature was kept at a constant value of 25 °C. As shown in Fig. 11(a), the power tracking of the proposed method turned out to be fast and accurate in finding the right direction, whilst that of the conventional P&O algorithm was lost when the solar irradiance changed rapidly. As a result, the latter method takes a longer time than the proposed one to address the phenomenon of the drift problem, as shown in Fig. 11(b).

In addition, the duty cycle of the proposed method is more accurate in finding the new MPP after solar irradiance changes, and it has a smooth oscillation around this value for steady-state conditions when compared with the conventional P&O-MPPT, as shown in the zoom in of Fig. 11(c). Consequently, the output power of conventional P&O-MPPT and the proposed method at the steady-state condition, after they reach to the MPP, are 100.722 kW and 100.724 kW, respectively, as shown in the zoom in of Fig. 11(a).

In the second scenario, the proposed method and the conventional FL-MPPT algorithm were simulated under the same weather conditions as previously. The simulation results again proved that the proposed method avoids the system experiencing the drift problem. In addition, it gives a fast response to finding the new MPP during a high change in solar irradiance, whereas the FL-MPPT continues to suffer from the drift problem, as shown in Fig. 12. However, this problem was more effective on the conventional P&O-MPPT than the conventional FL-MPPT, as shown in Figs. 11(b) and 12(b). Whilst the fluctuations of the MPPT tracker around the MPP steady-state conditions are higher in the proposed method when

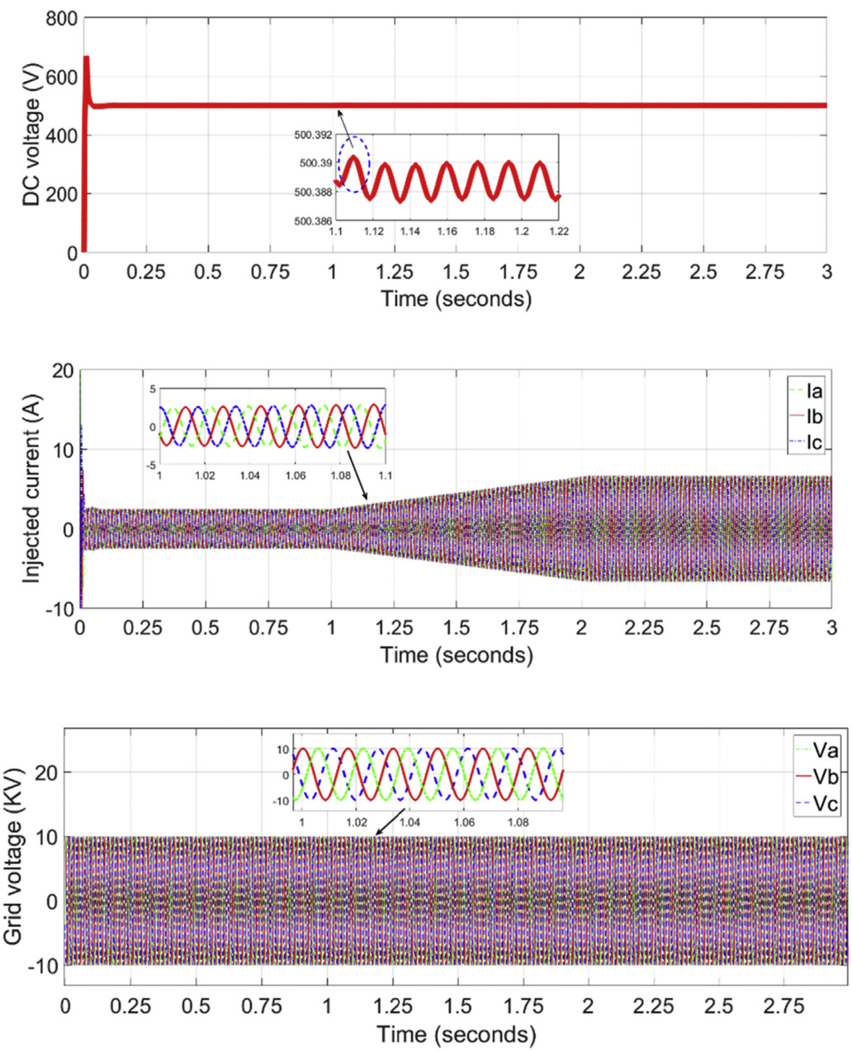

Fig. 13 – Grid-connected PV system using the proposed MPPT method: the DC voltage, the grid voltage and the injected current to the grid.

compared with the conventional FL-MPPT, as shown in the zoom in of Fig. 12(c), the output PV power of the conventional FL-MPPT is lower due to it having more membership functions, thus resulting in a longer computation time. Consequently, the lost power is a higher in the conventional FL-MPPT than the proposed MPPT method. As a result, the outputs under the steady state condition being 100.723 kW and 100.724 kW, respectively, as shown in the zoom in of Fig. 12(a).

To validate the accuracy of the proposed MPPT tracker for the grid-connected PV system, DC voltage, injected current and grid voltage, before and after the weather conditions change, were simulated. As shown in the zooming in of Fig. 13(a), the output voltage of the DC-DC boost converter is stable even during rapid weather conditions change as the one cycle at 1.1 s. Hence, the injected current and the grid voltage of the grid-connected PV system is stable at all times, as shown in Fig. 13(b) and (c). As a result, the proposed method is more effective for working with the grid-connected PV system under varying weather conditions. To assess further the proposed MPPT technique, Table 4 compares its properties with the conventional P&O-MPPT and FL-MPPT methods. As can be seen, the proposed MPPT method has a medium oscillation around the MPP point under the steady state condition, less number of fuzzy rule subsets, simple implementation and the highest output power. Moreover, according to the simulated results, the proposed technique accurately tracks the MPP and avoids the drift problem.

The EN 50530 standard test of MPPT efficiency

To assess the proposed method, The EN 50530 standard test of MPPT efficiency [47] was used. Basically, it involves supplying triangular waveforms of irradiance sequentially with different ramp gradients. The first sequence is a slow change of irradiance and then, this is gradually increased. In this work, three triangular sequences were applied, slow, fast and very rapid change in solar irradiance about 10, 40 and 80 W/m^2/s,

Table 4 – A comparison of the properties of the proposed method, conventional P&O and conventional FL.

MPPT	Number of fuzzy rules	Oscillation	Implementation	Output power (kW)
Proposed method	16	Medium	Simple	100.724
Conventional FL	25	Low	Complex	100.723
Conventional P&O	–	High	Simple	100.722

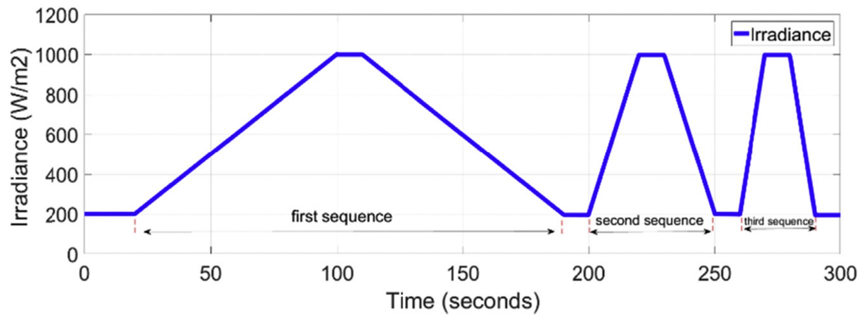

Fig. 14 – Triangular waveforms of irradiance for the EN50530 standard test of MPPT efficiency.

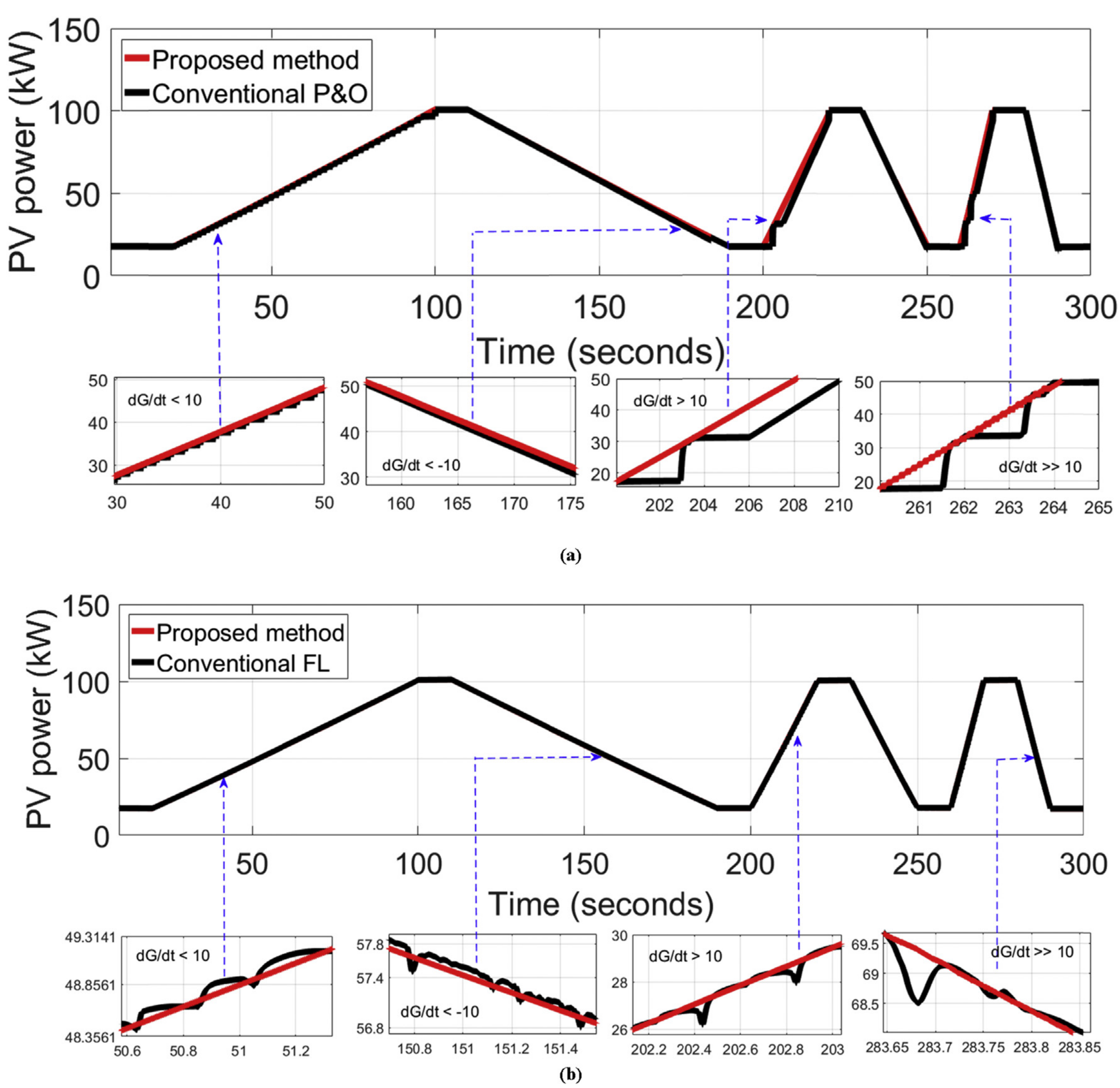

Fig. 15 – (a) MPPT power tracking for P&O versus the proposed method, (b) MPPT power tracking for FL versus the proposed method.

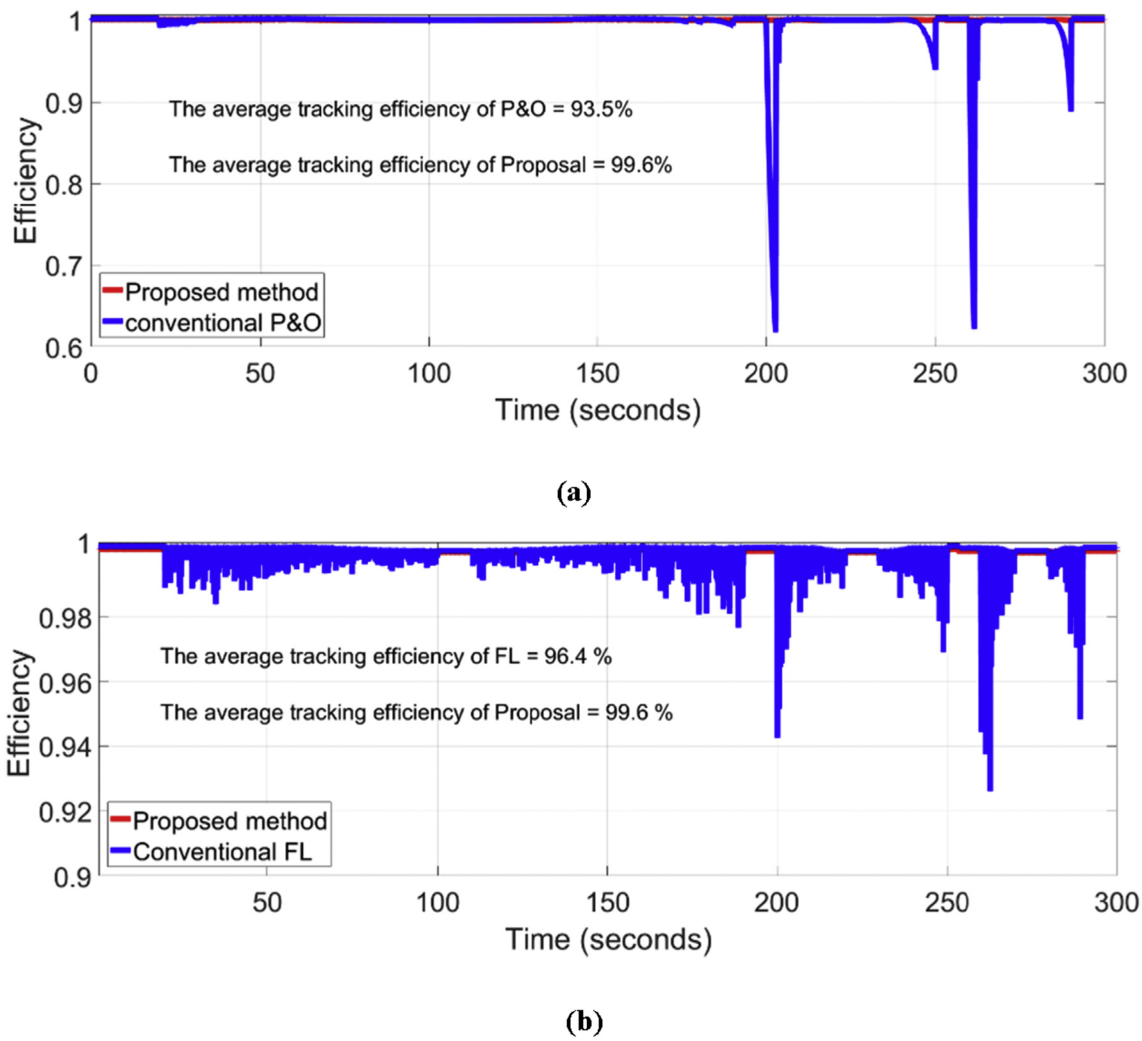

Fig. 16 – The average efficiency of power tracking under the EN50530 standard test for: (a) P&O-MPPT versus the proposed method; and (b) FL-MPPT versus the proposed method.

respectively, as shown in Fig. 14. The comparison between the proposed method and the conventional P&O method is shown in Fig. 15(a). Clearly, the tracking power of the latter is almost as good as the former during a slow change in the solar irradiance $(\Delta G < 10\ W/m^2/s)$ due to the large and fixed step size of the duty cycle, as show in first sequence, which is zoomed in on. However, the tracking power of the conventional P&O method drifts away from the right direction when the irradiance increases at a fast pace in second sequence $(\Delta G > 10\ W/m^2/s)$, as shown in the second zoomed sequence, because the MPPT tacking is not able to cope with the changes. In third sequence, the problem becomes a much more dramatic, i.e. when the irradiance is increased very rapidly $(\Delta G \gg \Delta 10\ W/m^2/s)$, as shown in the zooming in of the third sequence. In case of decreasing irradiance, the tracking power addresses the right direction under different sequences, as shown in the other side of the first sequence, which is zoomed in on. The comparison between the proposed method and the conventional FL method is shown in Fig. 15(b). Whilst the latter suffers from the drift problem under fast changes in weather conditions (increasing and decreasing the input solar irradiance), as show in Fig. 15(b), which is zoomed in on, the problem is a minimal when compared to the conventional P&O method. This is because the MPPT tacking of the conventional FL method can address the problem early. However, the problem became a much worse when the irradiance changes very rapidly. In contrast, the proposed method avoids the drift problem for all three ramp gradients, as shown in Fig. 15(a) and (b) which are zoomed in. To calculate the average tracking efficiency of the MPPT controller, the MPPT efficiency formula is used, as shown in Eq. (21) [45]:

$$\eta \cdot MPPT(avarge) = \frac{\int P_{out}(t)dt}{\int P_{max}(t)dt} \tag{21}$$

where P_{out} is the output power of the PV array and P_{max} is its theoretical maximum power. The actual power is calculated using the PV array current and voltage sensors. The theoretical maximum power calculated using Eqs. (1)–(4). The tracking time (t) is calculated according to the ability of the power tracking to reach the MPP under varying weather conditions. Whilst the MPPT efficiency of the proposed method for 400 W/m^2 appears to be lower, it achieves an average tracking efficiency of 99.6% under all the varying weather condition scenarios, whereas those for the conventional FL and P&O-MPPT methods are 96.4%, and 93.5%, respectively, as shown in Fig. 16.

Conclusion

A novel maximum power point tracking technique based on fuzzy logic for a grid-connected PV system has been presented, which has the ability to track the MPP when there are big fluctuations of irradiation. The advantages and disadvantages of the FL-MPPT and P&O-MPPT have been discussed. The designed membership functions of FL the controller where tuned based on modified a P&O algorithm to incorporate the advantages of the P&O-MPPT and the FL-MPPT as well as to eliminate their drawbacks. A MATLAB-SIMULINK model for the grid-connected PV system was developed. The P&O-MPPT, FL-MPPT, and proposed method were simulated, being then compared, according to their common features. The EN 50530 standard test was used to calculate the efficiency of the proposed method under varying weather conditions. The simulation results have revealed that the proposed technique exhibits higher output power, medium oscillation around the MPP point under the steady state condition and no divergence from the MPP during varying weather conditions regardless of the speed of change. That is, the proposed concept has been demonstrated to be highly effective for working with a grid-connected PV system, achieving efficiencies of around 99.6%. Finally, this modification has been shown to be simple to implement.

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