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Comparing the Performances of MPPT Techniques for DC-DC Boost Converter in a PV System

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Abstract

The paper presents a comparison in terms of the performance of 3 maximum power point tracking methods used to achieve maximum output power from a photovoltaic system under varying irradiance. The maximum power point techniques considered in this study were Perturb and Observe, Incremental Conductance and Fuzzy logic. A literature review of related studies was conducted and a photovoltaic module modeling was presented. Moreover, a detailed theory of boost converter was also given. These 3 methods were discussed in detail and their flowcharts were presented. Simulation results from MATLAB/SIMULINK demonstrated a comparison between the 3 maximum power point tracking strategies. Results of current, voltage, and power from the photovoltaic module and the boost converter showed that the Fuzzy logic maximum power point tracking method had the best performance compared with other techniques.

Keywords: Performance comparison, Maximum power point tracking, Photovoltaic, Renewable energy, Power system

Introduction

The world is facing an energy crisis because most of the power is still generated by conventional generators using expensive fossil fuels. Utilities around the world have been working hard in the past few decades to replace conventional generations with power from distributed energy resources to reduce cost, pollution, and other environmental problems caused by generators using fossil fuels. Among many, solar photovoltaic (PV) has become one of the leading power generation replacing old and costly conventional generation due to its cleanness, safety, long life, low maintenance, cheapness, and availability [1]. There are currently many standalone and grid-connected solar power plants functioning around the world.

A solar power plant can be interfaced with an AC microgrid or a large power system using DC/AC converters or DC loads/microgrid via DC/DC converters [1]. A typical configuration of a 3-phase grid-connected PV system is shown in **Figure 1**. It consists of a solar array, a 3-phase inverter, the filter inductor, and a 3-phase grid voltage source. The 3-phase inverter with filter inductor converts a DC input voltage into an AC voltage employing appropriate switch signals to make the output current in phase with the utility voltage and obtain a unity power factor. The configuration consists of 2 main controllers; the DC-side controller for the boost DC/DC converter and the inverter's AC-side controller. The DC/DC converter is controlled to maintain the fixed DC link voltage high enough to make the inverter operate to achieve the PV array's maximum power.

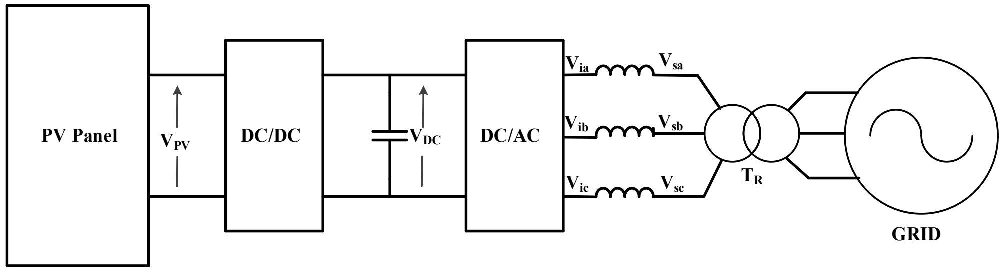

Figure 1 The connection of the PV module to the power system.

To optimally track all the PV module's available power, the PV system employs maximum power point tracking (MPPT) methods. These methods control the PV system operation by sending gate signals to the DC-DC boost converter. Therefore, choosing a suitable control mechanism for the boost converter is of great importance for power system engineers to achieve effectively and cost-competitiveness to optimize the PV system efficiency.

In the last decade, many MPPT techniques have been studied regarding their differences in speed, accuracy, and complexity, where 3 aspects of interest are usually evaluated: Demands of the PV module's physical information, usage of computing capability, and efficiency. There is an extensive list of publications from those studies.

Authors in [2] compared 3-point P&O and Hill Climbing (HC) methods for MPPT. In this study, both methods are explained in detail, including the flowchart of each method. The difference between the conventional 2-point P&O and the 3-point P&O is described. Sudden changes in temperature and radiation are included as disturbances when testing the methods. Simulation is performed when the PV panel is at different radiations with a fixed temperature of 25 ºC and different temperatures with fixed radiation of 1,000 w/m^2. The results obtained show the robustness of the 3-point P&O method over the HC. The performance criteria checked are the power fluctuations and the maximum PowerPoint.

Modeling, simulation of MPPT methods using P&O, and IC techniques for stand-alone PV systems are presented in [3]. Simulink block diagram of the main components of the stand-alone PV, P&O technique, and IC are shown. The equivalent circuit of the PV model is discussed. The P&O method and IC methods are explained in detail, tested, and their results compared under different sunlight and cell temperatures. Additionally, it demonstrates the PV array's supply power with the P&O and Incremental Conductance MPPT technique compared with the case when the MPPT technique is disabled.

In [4] the current control based (CCB) MPPT technique is compared with the conventional P&O MPPT technique. In the paper, the mathematical modeling of the PV power generation system is presented. Both methods are explained in detail, then compared in terms of the results of power, current, and a voltage obtained from simulations performed in MATLAB/Simulink. Results collected show that CCB MPPT has low oscillations and a smoother speed of response.

Incremental conductance, FLC, and artificial neural network (ANN) are discussed and used to track the PV array's maximum power point, and their results are compared in [5]. The parameters used for comparison are the output voltage, current, and power. The test is conducted on different irradiation levels from 1,000 w/m^2 to 200 w/m^2 at a constant temperature. There is a mixed reaction in the results obtained as FL-MPPT shows robustness at higher irradiations (1,000 - 700 w/m^2), IC-MPPT at lower irradiations. There is also a similarity in the results of the FL-MPPT & ANN-MPPT.

Authors in [6] incorporate a real twisting algorithm (RTA) and super twisting algorithm (STA) in the higher-order sliding mode control (HOSMC) to enhance its superiority to control a non-inverting DC to DC buck-boost converter experiencing varying weather conditions, faults, and uncertainties. This method is compared with the proportional-integral-derivative (PID) and P&O in terms of tracking speed and efficiency. In the paper, the mathematical model and reference voltage generation procedures are discussed in detail. The results obtained show the robustness of the proposed technique over the other methods.

The P&O results, modified, and conventional variable step-size IC are presented and compared in [7]. In the paper, the grid-connected PV system is configured and modeled. The 4 methods are discussed, and their results are compared based on efficiency and response time. Confusion faced by conventional algorithms is discussed. Results show that the proposed method responds and tracks the MPP accurately than the other methods. Additionally, the method does not show steady-state oscillations and reduces power losses.

In [8] a comparison of 3 widely used MPPT algorithms is conducted by simulations from MATLAB Simulink. The methods are P&O, particle swarm optimization (PSO), and cuckoo search (CS). Simulations are performed under standard test conditions (STC) and varying irradiance. The research objective, system description, discussion on the MPPT techniques and results obtained are part of this work. The performance is checked for efficiency, time, and accuracy. The CS method shows the best performance.

A test conducted in Alvalade, Lisbon (Portugal) for the 2 MPPT controllers' performance, one being fixed step size IC MPPT and the other variable step size Neuro-Fuzzy IC MPPT gave the results that the latter outperforms IC-MPPT [9]. The proposed method improves the output power and reduces power losses.

In [10], a method is presented with the highest accuracy and shortest response time compared to P&O, IC and FLC. A brief description of the proposed method can be found in this study. The results show that the proposed method is 4 times faster than P&O and 5 times faster than IC, and approximately 28 % faster than FLC. Additionally, it has higher efficiency and tracking capability and low steady-state error.

Five MPPT techniques are tested for 5 different weather cases, and their results are compared in [11]. The methods discussed are Salp-sarm optimization (SSO), Artificial Bee Colony (ABC) optimization, PSO, PSO-gravitational search (PSOGS), Dragon-fly optimization (DFO), CS optimization, and P&O algorithms. Results obtained prove the robustness of the proposed SSO technique against other methods by giving higher efficiency, speed, and stability.

The above studies have extensively shown the superiority of fuzzy logic and weaknesses of conventional P&O as MPPT techniques, with Incremental conductance standing between them. Some research works have shown that the effectiveness of many MPPT techniques can be improved by applying different methods to increase their robustness. Moreover, the studies show that hybrid techniques like ANFIS produce better results than their original counterparts.

In contributing to the existing studies, this study presents 3 MPPT techniques known as Perturb and Observe, Incremental Conductance, and Fuzzy logic to control a boost converter. The methods are discussed in detail, tested with the PV system, and their results are compared. The rest of the paper is organized as follows: Section 2 presents the PV module modeling, followed by a detailed explanation of the boost converter in section 3. A general overview of MPPT techniques followed by a brief description of each MPPT method is found in section 4. Simulation results and discussion are presented in Section 5, and finally, the last section concludes this paper.

Materials and methods

PV module modeling

Solar cells for PV arrays are usually connected in series/parallel combinations. A simplified PV cell equivalent circuit is shown in **Figure 2**. There is a current source, a shunt diode D and a series resistor R.

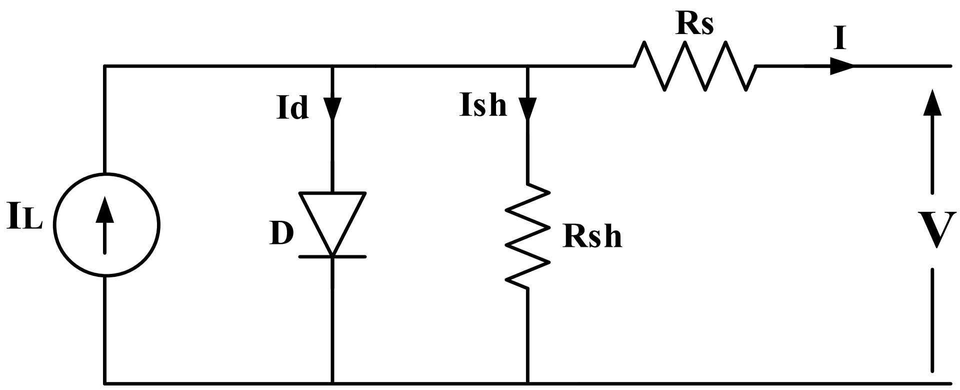

Figure 2 One - Diode model of a PV cell.

The electrical characteristic equation of the PV cell for a Shockley diode is,

$$I = I_{ph} - I_D = I_{ph} - I_0 \left(e^{\frac{q(V_a + IR)}{nkT_a}} - 1 \right) \tag{1}$$

where,

I : Current of the PV cell

I_0 : Saturation current of the diode.

I_{ph} : Photocurrent.

q : Elementary charge, = 1.60217646×10 - 19 C.

n : The diode ideality factor.

k : Boltzmann constant, = 1.3806503×10 - 23 J/K.

T_a : Ambient temperature.

V_a : Terminal voltage of the PV cell.

DC-DC boost converter

Solar photovoltaic produces DC power. This power is in a small amount; therefore, extracting the maximum available power from the PV system is of great concern. A suitable control mechanism is needed for a DC-DC boost converter to fulfill this requirement, which is responsible for the output DC voltage stability. The input to the boost converter is the solar PV which its output highly depends on solar irradiation and temperature. Boost converter output voltage can be affected by the variation of load and input PV voltage. Different control strategies have been applied to control boost converters for the PV system's maximum power output. The circuit diagram of the boost converter connected to the PV module is shown in **Figure 3** [12,13]. The switch S_1 is controlled to open and close periodically, making the boost converter produce an output voltage greater than the input voltage. The boost converter behaves like an inductor storing the energy in its magnetic field and releases it.

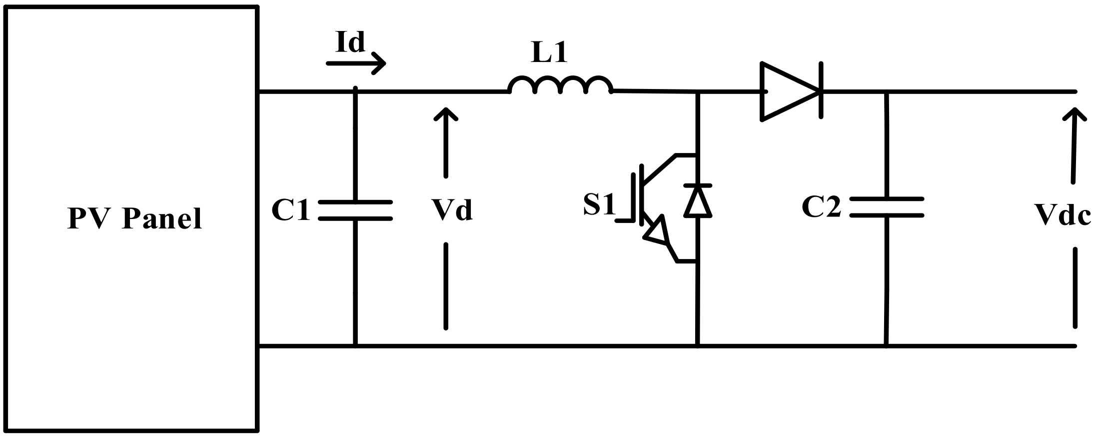

Figure 3 The PV module and the internal structure of a boost converter.

Maximum power point tracking (MPPT)

To maximize the output power of the PV module, the system should operate at its maximum power point (MPP). Solar irradiation and the temperature of the module are the main factors affecting the MPP. These parameters are time-varying. Usually, the load curve of the PV module or string is controlled to intersect $I-V$ the curve where $i_{PV} \times v_{PV}$ is maximum. This situation occurs at maximum power voltage $v_{MP}\left(v_{PV}=v_{MP}\right)$, which is the reference input of the control system. Solar irradiation and the module temperature measurements could be used to compute, but the cost of solar irradiation sensors makes it impossible. Numerical methods are used instead, to minimize the costs. These methods are known as MPP tracking (MPPT) methods.

Extensive research has been done on MPPT methods classified in **Figure 4**. Several MPPT methods can be found in practice and the literature [14-17]. These techniques are capable of reaching up to 99 % of the MPP efficiency. In the paper, 3 MPPT methods [18] are discussed in detail and compared in terms of their performance.

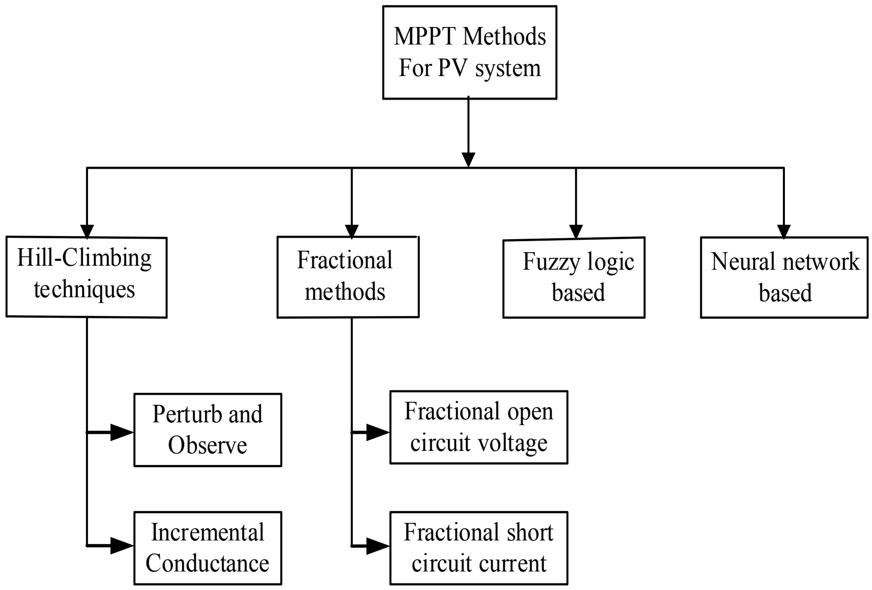

Figure 4 MPPT algorithm classification.

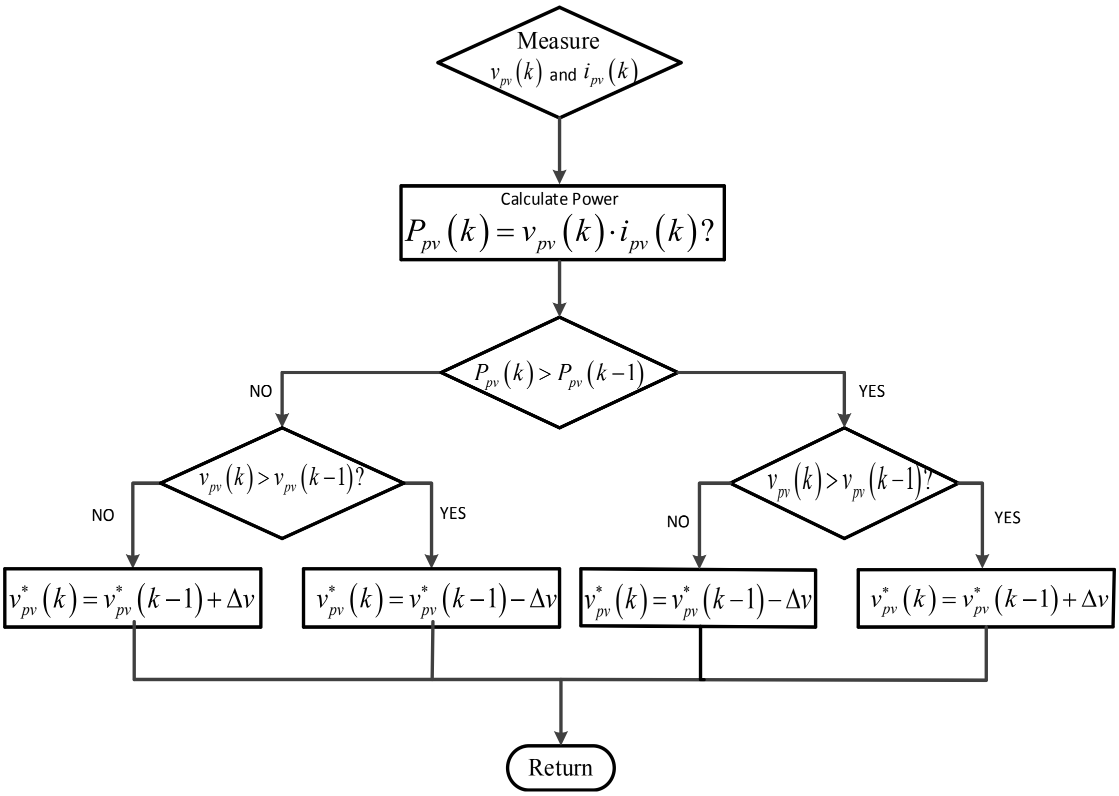

Figure 5 P&O algorithm.

Perturb and observe (P&O)

To reach MPP, this method (which is a Hill-Climbing technique) is based on a continuous reference voltage search process, as shown in **Figure 5**. In the process, the reference voltage is perturbed, and the system response is observed. This determines the direction of the next perturbation. The reference voltage perturbations are performed in such a way that the power should increase [19,20].

Incremental conductance

The slope of the power curve can be computed by the following 1st-order differential equation,

$$\frac{dP_{PV}}{dv_{PV}} = \frac{d\left(i_{PV} v_{PV}\right)}{dv_{PV}} = i_{PV} + v_{PV}\frac{di_{PV}}{dv_{PV}} \tag{2}$$

This gives,

$$\frac{dP_{PV}}{dv_{PV}} = i_{PV} + v_{PV}\frac{di_{PV}}{dv_{PV}} \tag{3}$$

The maximum power is obtained when L.H.S derivative is zero as,

$$\frac{dP_{PV}}{dv_{PV}} = 0 \Rightarrow \frac{di_{PV}}{dv_{PV}} = -\frac{i_{PV}}{v_{PV}} \tag{4}$$

where:

i_{PV}/v_{PV} = the conductance

di_{PV}/dv_{PV} = the incremental conductance.

The derivative of the current to the voltage can be approximated as the difference between the actual values and the previous instant values in that iteration process. Hence, by comparing the conductance i_{PV}/v_{PV} to the incremental conductance di_{PV}/dv_{PV} as shown in **Figure 6,** the algorithm can track the MPP and stay there until a change of di_{PV} or dv_{PV} occurs as a result of a change in atmospheric condition [21].

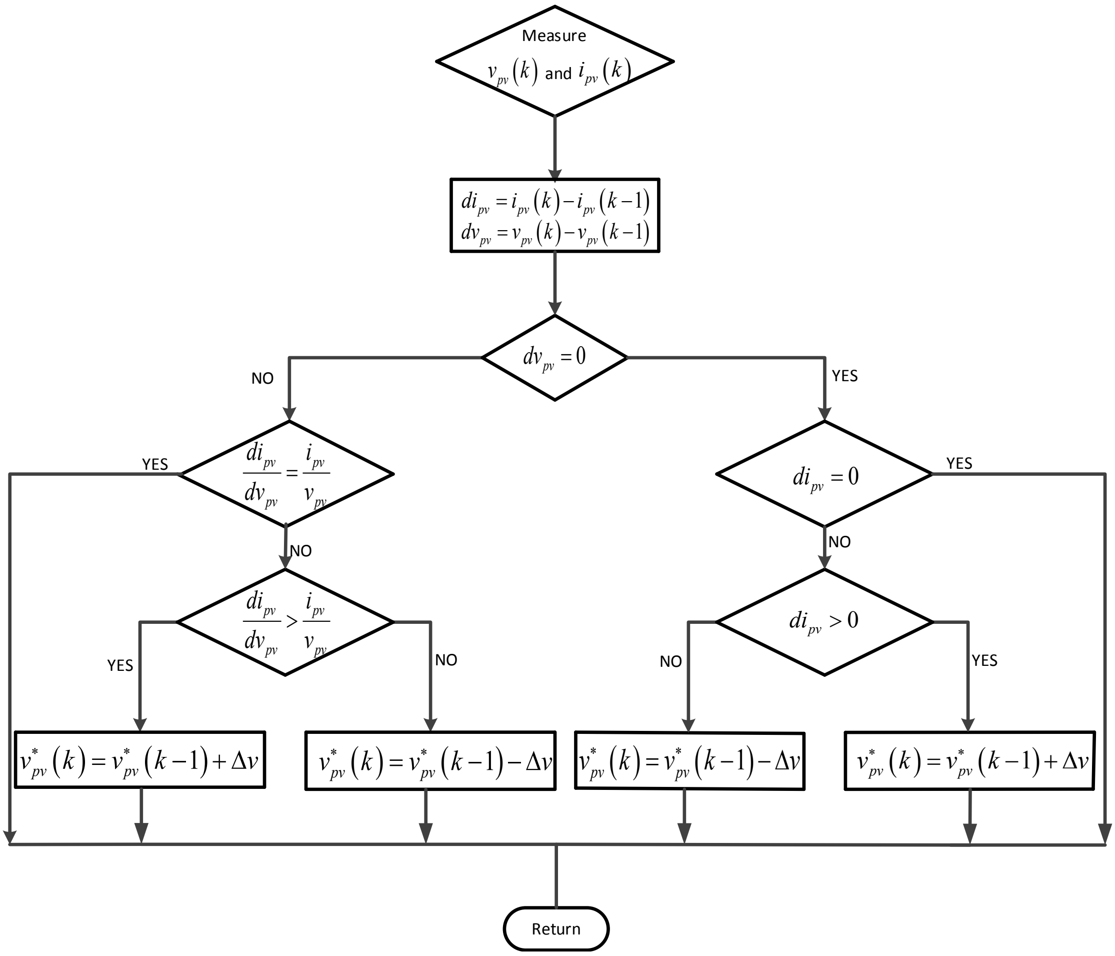

Figure 6 Incremental conductance MPPT algorithm.

Fuzzy logic control

The FLC monitors the output power of a PV module at each sample time t. The method can be easily implemented. FLC based MPPTs have been an active research area for the PV system among many researchers [22-30]. The strategy does not require knowledge of the exact PV module system. It can be applied to control both linear and nonlinear systems even under various atmospheric conditions.

The inputs to the FLC are an error e, and the change in error Δe and the output is the duty cycle (D). This output is sent to the pulse width modulation (PWM) to control the DC-to-DC converter.

$$e(t) = \frac{p(t) - p(t-1)}{v(t) - v(t-1)} \tag{5}$$

where:

e = the error

$P(t)$ = the instant power of the photovoltaic generator.

$$\Delta e(t) = e(t) - e(t-1) \tag{6}$$

where Δe = change in error

The error and change in error signals as inputs for the fuzzy logic controller are shown in **Figure 7**.

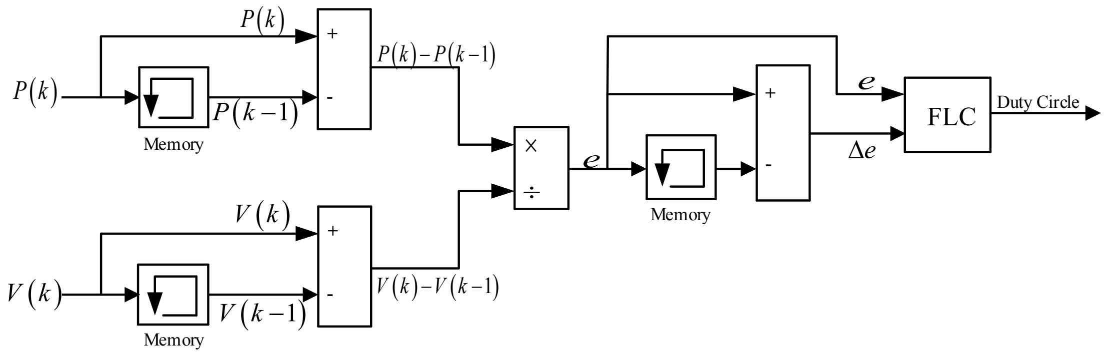

Figure 7 Generating error and change in error signals.

The fuzzy logic controls the duty cycle of the boost converter to get the maximum power point tracking, and the converter boosts up the level of voltage depending upon the duty-cycle. **Table 1** shows the input/output variables articulated in seven linguistic labels, Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), Positive Big (PB).

Table 1 Rules for the fuzzy logic controller.

$e/\Delta e$	**NB**	**NM**	**NS**	**ZE**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PB	NM	ZE	ZE
NM	PB	PB	PB	PM	PS	ZE	ZE
NS	PB	PB	PS	PS	PS	ZE	ZE
ZE	PB	PM	PS	ZE	NS	NM	NB
PS	ZE	ZE	ZE	NS	NS	NM	NB
PM	ZE	ZE	NS	NM	NB	NB	NB
PB	ZE	ZE	NM	NB	NB	NB	NB

The fuzzy inference is processed using Mamdani's method. Defuzzification uses the center of gravity method to process output which is the duty cycle.

Results and discussion

In this study P&O, IC, and FL MPPT methods are used under the following conditions: Irradiance = [1,000 - 800 - 600 - 400 - 200] w/m^2 at a fixed temperature of 25 ºC as in [5]. **Figures 8 - 13** below show the output voltage, current, and power of the PV and boost converter when using P&O, IC, and FL MPPT methods. The results in **Figures 8 - 13** show that the voltage, the current, and the power output from the PV module and the boost converter when using fuzzy logic as an MPPT method are the highest and stable compared to the ones from IC and P&O methods, IC being the 2nd-best [31]. In this research and the one conducted in [31], the voltage, current, and power of the boost converter (**Figures 11 - 13**) have fewer oscillations compared to the output of the PV for all the methods applied. This research and the one in [32] give similar results for the PV output power (**Figure 10**) as in both cases FL-MPPT extracts the most power from the PV module followed by IC-MPPT, and P&O being the lowest. The results for PV output power (**Figure 10**) in this work are similar to some results in [33] where the fuzzy logic method extracts more power than the P&O technique. FL-MPPT again shows its superiority in extracting the most power in [34], echoing all the results obtained in this study. Perturb & Observe method shows weaknesses in terms of the magnitude of the output power, voltage, and current in [35], similar to the situation experienced in this research. The power extracted from the PV module with a fuzzy logic-based method (ANFIS) is higher and stable than the one obtained from P&O in the research performed by [26] matching the results in this study. FL-MPPT, IC, and P&O are also compared in [28] and show the same behavior as in this work. Perturb & Observe method experiences the most oscillations in its plots and slow response, followed by IC as compared to the FL-MPPT. Authors in [36] compare FLC-MPPT and P&O techniques in terms of their performance as in this research. Results obtained after simulations show that when applying FLC as MPPT ripples and oscillation rates of the output power is lower than those occurring when the MPPT method is P&O making FLC more suitable for practical implementation. Fuzzy logic shows its superiority over IC in [37] as in this study. The method forms a hybrid MPPT technique with IC named INC-Fuz to extract maximum power from the PV. This method INC-Fuz is faster than conventional IC to reach steady-state values of output power and voltage. Fuzzy logic MPPT shows its effectiveness in terms of performance over P&O in [38] as in this research. An increased accuracy and tracking capability of the MPP and the reduced steady-state oscillations due to the application of FLC-MPPT in [39] compared to P&O are similar to the results obtained in this research.

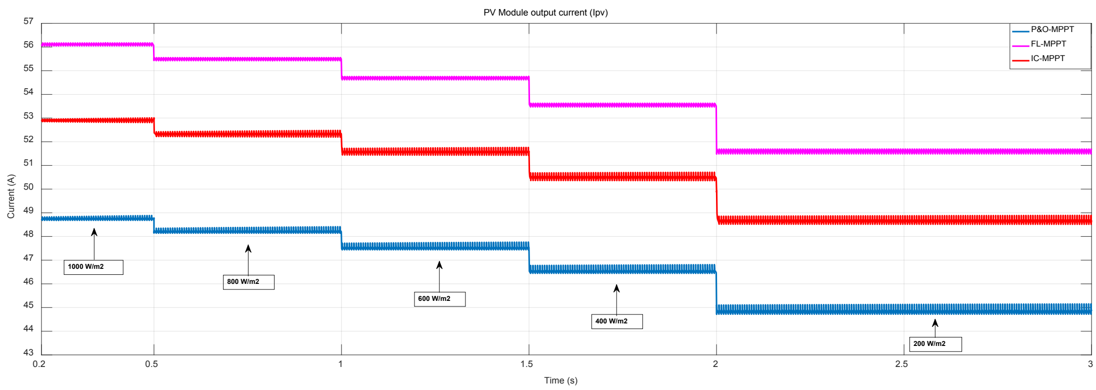

Figure 8 Output current of the PV Module.

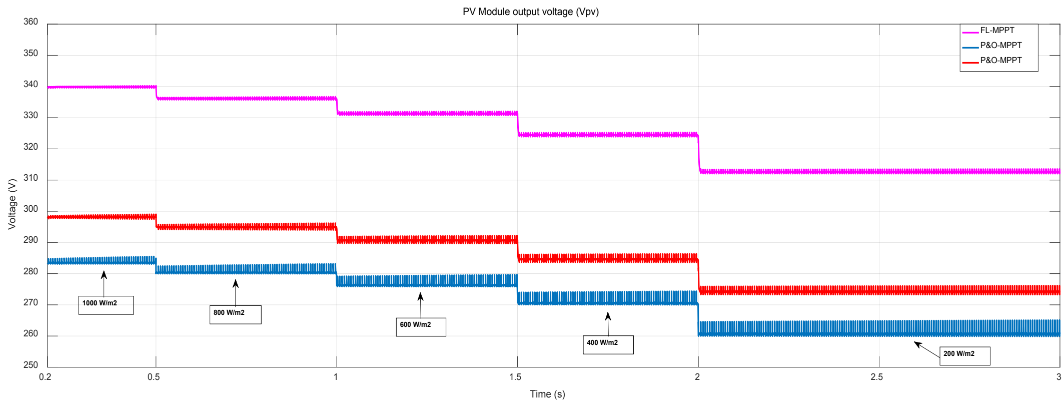

Figure 9 Output voltage of the PV Module.

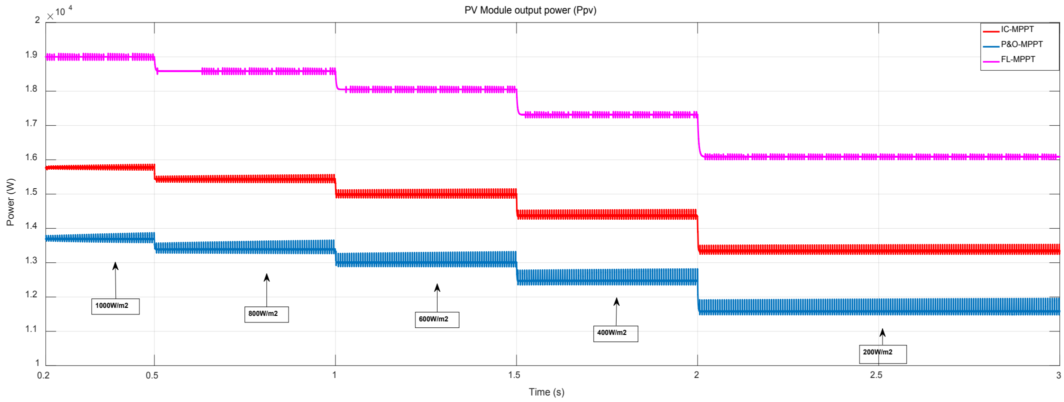

Figure 10 Output real power of the PV Module.

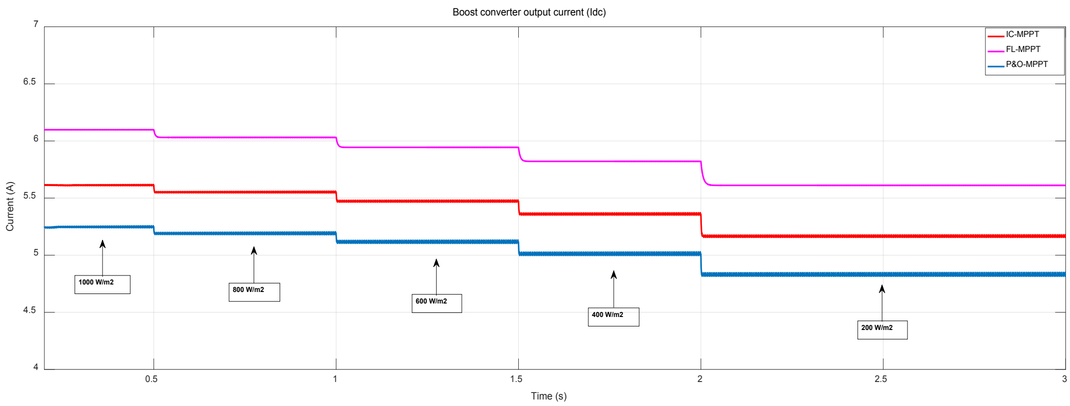

Figure 11 Output current of the boost converter.

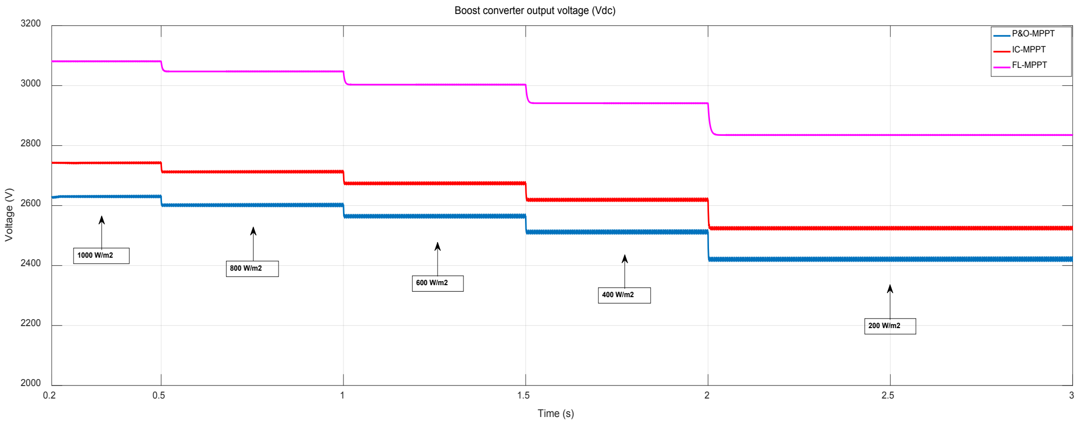

Figure 12 Output voltage of the boost converter.

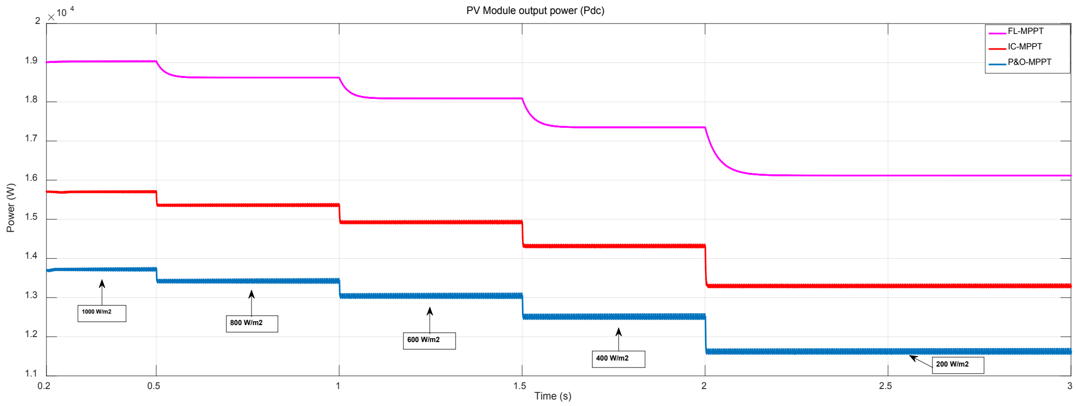

Figure 13 Output real power of the boost converter.

Conclusions

This paper has compared the performances of 3 MPP methods in terms of their performances. The parameters used to verify the effectiveness of the methods are the output voltage, current, and real power of the PV module and the boost converter. In the paper, Perturb and Observe, Incremental Conductance and Fuzzy logic methods have been explained in detail and applied to control the PV system's boost converter. Results obtained from simulations in MATLAB/SIMULINK show that the MPPT controller developed using FLC is robust. The fuzzy logic MPPT method has managed to output the greatest amount of voltage, current, and real power from the PV and boost converter. Besides, as seen from the plots provided, all the parameters have the highest stability with FL-MPPT, followed by IC, P&O being the poorest.

Acknowledgments

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