Performance of Fuzzy MPPT for a Distributed Photovoltaic System Under Changing Environmental Condition

P. Rajakumar, M. Senthil Kumar, A. Sakthidasan, R. Sundar, Baburao Pasupulati, and S. Amosedinakaran

Abstract In recent times, power generation through distributed generation (DG) technique is increasingly adopted around the globe. Particularly photovoltaic (PV)-based DG has been used widely because of the vast availability of solar energy. However, the electrical power delivered by PV cells varies since their characteristics are completely dependent on ambient factors. As a result, having a unique technique to extract the maximum power available from sun irradiation is critical. Such a technique is known as maximum power point tracking (MPPT). In the present study, a simulation analysis is performed on a 5 kW standalone DG PV plant using a fuzzy controller-based MPPT technique. The performance of fuzzy MPPT techniques is evaluated under distinct operating conditions. The simulation study is then extended to include perturb and observe (P&O) technique to evaluate the effectiveness of the fuzzy MPPT controller. The comparative study revealed that fuzzy MPPT provided better results. The simulation investigation is carried out using MATLAB/Simulink software version 2020a.

Keywords Distributed generation · Maximum power point tracking · Fuzzy controller · Photovoltaic system

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1 Introduction

The usage of alternative sources of energy has increased in recent times to meet the ever-growing electrical demand. This is mainly due to compensate for the increase in fuel cost and emission of greenhouse gases. Also, many countries insist on giving incentives for motivating the use of renewable-based power generation. This made a tremendous change in the adoption of renewable energy in the residential and commercial sectors. Among the available resources of renewable energy, solar photovoltaic system is the most popular and prepared one since the source of energy for PV systems is clean and abundant. Because of this, it has been widely used in residential, commercial and industrial purposes. Even solar powers have been utilized for military purposes. Generally, solar power generation ranges from a few kW to large MW systems. In large solar power plants, power loss occurs between generating stations and consumers through transmission and distribution lines. Due to the poor conversion efficiency of solar cells, the cost of the solar plant will increase even further. To reduce the losses, it is preferred to have a power generation closer to the consumer load side. Such a concept is known as distributed generation. A distributed generation is a concept where the power generation is located closer to or on the load centre. Distributed generation uses various sources of energy for the generation of power near load centres. Among them, solar power is widely preferred because of its availability and environmental sustainability [1–3].

Due to the poor conversion efficiency of solar cells, it is essential to have some unique and efficient technique to avail maximum source of power from PV cells under given condition. The power generated from a single PV cell purely relies on factors such as angle of sunlight incident, solar irradiance, environmental temperature and type of load. The typical characteristic curve of a PV cell is nonlinear since its output depends on available irradiance and ambient temperature at a particular location. Due to this nonlinear behaviour of a PV cell, the output power fluctuates in accordance with environmental factors. As a result, MPPT is used between solar PV systems and load/inverter to improve PV cell conversion efficiency. Also, MPPT accommodates a DC-to-DC power converter for effective transfer of power from PV system to load/inverter at required voltage level. MPPT and DC-to-DC power converter help together to achieve maximum power extraction from solar PV cells under given environmental conditions. MPPT can be implemented by changing the duty cycle of the semiconductor switch or by utilizing a closed-loop controller to regulate the PV voltage and current. A brief literature about the adoption of MPPT for PV systems is presented below.

References [4–9] numerous MPPT algorithms were adopted. Among these methods, P&O and InC methods are employed frequently because of its simplicity of design and implementation. Both the methods employ a fixed step size in the operating variable. In PV MPPT choice of step size variation plays an important role in achieving desired performance characteristics. If a small step size is adopted, then tracking speed gets reduced. On the other side, larger step size selection increased the tracking speed but the system experienced unnecessary power losses due to fluctuation of maximum power point (MPP).

An effective MPPT algorithm should have high tracking speed to reach MPP without producing fluctuation at steady state. For such a technique, adoption of variable step size could produce desired results. If the operating point is far from the target operating point, this strategy leverages larger step size variation in the operational variable. Similarly, smaller step size variation is adopted if the operating point is near the MPP region. This method enables MPPT to reach the desired operating point faster and with less oscillation at steady state. Artificial intelligent techniques are likely to adjust such step size variation according to the operating condition. Fuzzy logic and neurofuzzy systems have been addressed in [10, 11] for such applications. Moreover, FLC-based techniques can also be suitable for nonlinear systems. The important aspect of this FLC technique is that it does not require precise knowledge on the mathematical representation of the system to achieve the required control performance [12, 13]. This feature has made FLC-based MPPT an effective system in the solar energy management for better tracking of MPP. In this paper, a main focus is given on the implementation of FLC-based MPPT for standalone 5 kW DG PV plant. The performance of FLC MPPT is related to the conventional P&O method for different environmental factors.

The content of the remaining paper is presented as follows: Sect. 2 briefs about the PV system configuration. The concept of P&O and FLC MPPT techniques is presented in Sect. 3. In Sect. 4, the simulation test results of the P&O and FLC MPPT methods for various operating situations are presented and examined. Then, Sect. 5 summarizes the finding of this paper work as a conclusion.

2 PV System Configuration

Figure 1 depicts the overall system setup used in the present study. The PV system consists of a 5 kW PV array, a DC–DC converter, and an MPPT controller.

2.1 PV Array

A 5 kW PV array system is modelled for simulation using a single diode photovoltaic cell circuit model, as shown in Fig. 2 [14]. The mathematical description for output current (I_{PV}) of a single PV cell is given in (1).

$$I_{PV} = I_{SC} - I_O\left\{\exp\left[\frac{q(V + IR_S)}{nkT_K}\right] - 1\right\} - \frac{V + R_S I}{R_{SH}}, \tag{1}$$

where (I_{SC}, I_O) points to short circuit current and saturation current of PV cell; q reflects the electron charge; n and k refer ideality factor and Boltzmann's constant,

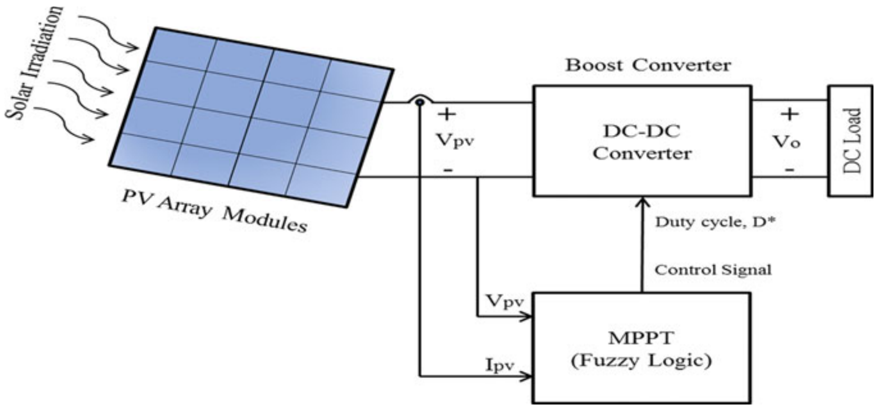

Fig. 1 Configuration of PV system

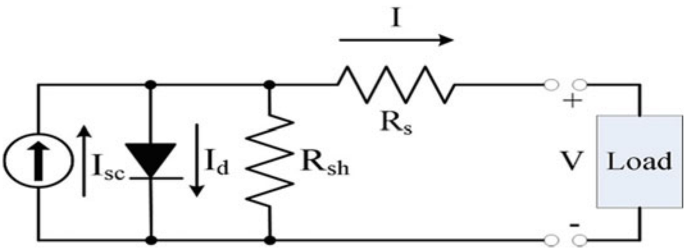

Fig. 2 Single PV cell equivalent circuit model

respectively; T_K is the PV cell temperature; (R_S, R_{SH}) denotes to equivalent series and shunt resistance.

From (1), it is inferred that output current of a PV cell depends on temperature and solar irradiance. In this work, a 5 kW PV array system is modelled using 1Soltech 1STH245WH PV module. Table 1 shows the electrical specification of 1Soltech 1STH245WH PV unit. The 5 kW PV system is modelled using PV modules from NREL System Advisor Model. A single 1Soltech 1STH245WH PV module can deliver maximum power of 245 W for a 1000 W/m^2 solar irradiance and 25 °C temperature. For modelling a 5 kW PV system, 21 PV modules are arranged in three parallel strings and each string carries seven series of connected PV modules.

Figures 3 and 4 show the characteristics of a 5 kW photovoltaic system under various operating circumstances. Figure 3a exemplifies the relation between P and V for variable solar irradiance level. Figure 3b demonstrates the correlation between I and V for the variable solar irradiance incident. Similarly, Fig. 4a and b illustrates the characteristic curves of PV array systems for variable temperature conditions.

Table 1 1Soltech 1STH245WH PV module electrical parameter

S. No	Parameters	Values
1	Open circuit voltage (V_{oc})	37.2 V
2	Maximum voltage (V_{pm})	30.2 V
3	Short circuit current (I_{sc})	8.62 A
4	Maximum current (I_{mp})	8.1 A
5	Maximum power (P_{mp})	244.62 W
6	Number of cells	60

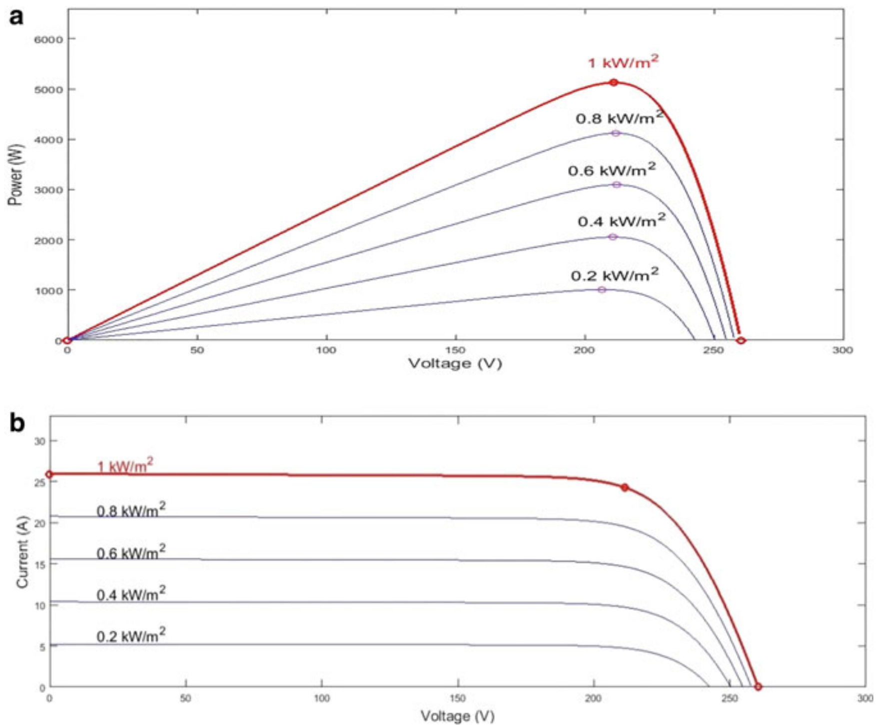

Fig. 3 **a** P–V characteristics for variable irradiance. **b** I–V characteristics for variable irradiance

2.2 Converter Circuit

The maximum power extraction from PV system is ensured through the connection of converter (DC–DC) in the middle of the solar photovoltaic system and the load or inverter circuit. A converter, on the other hand, varies the magnitude of PV output voltage to the necessary voltage level. A typical DC–DC converter is classified as buck, boost, or buck–boost. In this paper, boost converter topology is selected since the output voltage is fixed to 370 V. Equation (2) expresses the correlation between

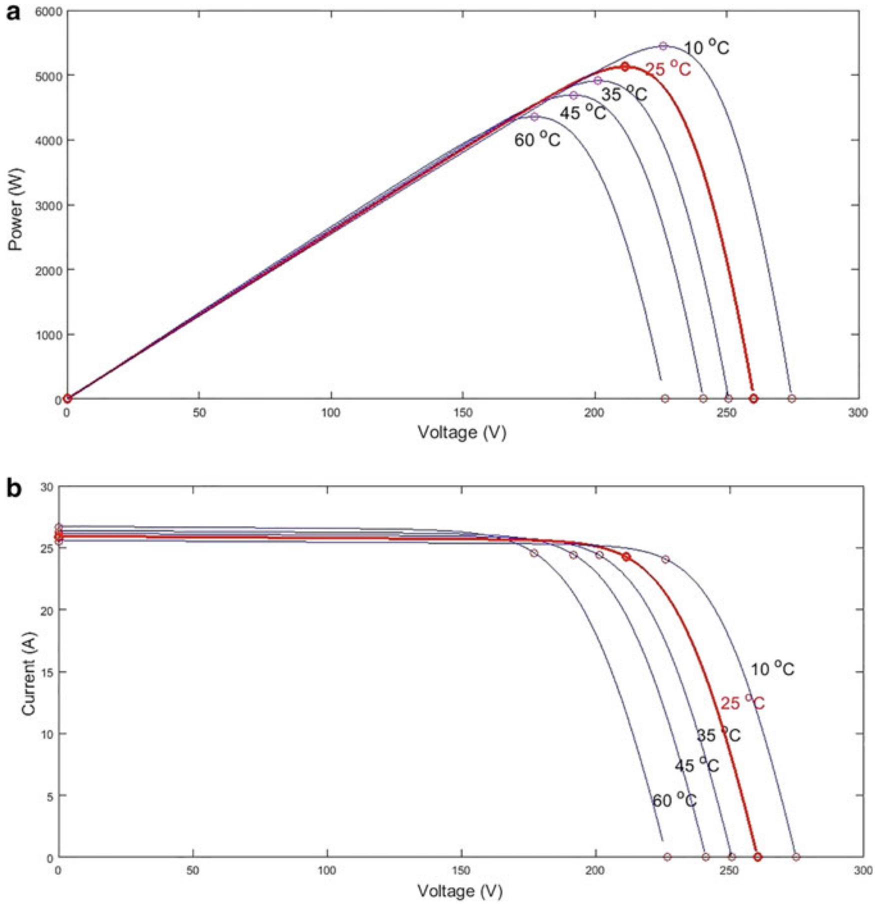

Fig. 4 **a** P–V characteristics for variable temperatures. **b** I–V characteristics for variable temperatures

input (V_{pv}) and output (V_O) voltage of boost converter.

$$\frac{V_O}{V_{PV}} = \frac{1}{1 - D} \tag{2}$$

where D refers to duty cycle.

Figure 5 and Table 2 show the circuit topology and design parameters for a boost converter, respectively.

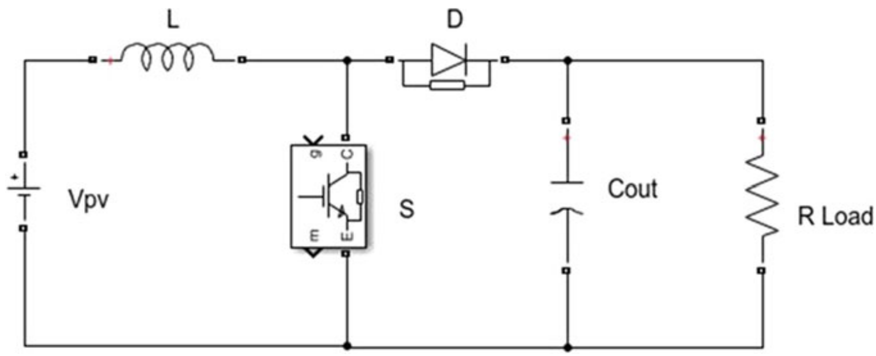

Fig. 5 Topology of boost converter

Table 2 Boost converter design parameters module electrical parameter

S. No	Parameters	Values
1	Input voltage, V_{pv}	180–210 V
2	Output voltage, V_O	370 V
3	Output capacitor, C_{out}	1000 μF
4	Inductor, L	470 μH
5	Switching frequency, F_s	10 kHz

3 MPPT Algorithm

The MPPT technology effectively extracts electricity from sunlight. P&O, InC and FLC approaches are three prominent and widely used MPPT strategies in PV systems [15]. In this article, fuzzy and P&O MPPT algorithms are used to test their effectiveness on a 5 kW PV DG unit under various climatic situations.

3.1 P&O MPPT Algorithm

It is a basic and widely used MPPT technique that works by changing the operational parameter. The operating parameter can be a PV array voltage or current. P&O algorithm functions by sampling PV array power for a sample time m interval. The PV array power of two consecutive sampling intervals of m and $(m - 1)$ is computed and related with each other. If the power of the PV array during the mth interval is greater than the power during the $m - 1$ interval, the operating parameter is sampled as the previous interval. If the difference of PV array power during two consecutive sampling intervals is negative, then direction of perturbation is reversed. The above process is repeated till the desired operating point. Figure 6 depicts the flowchart for P&O algorithm.

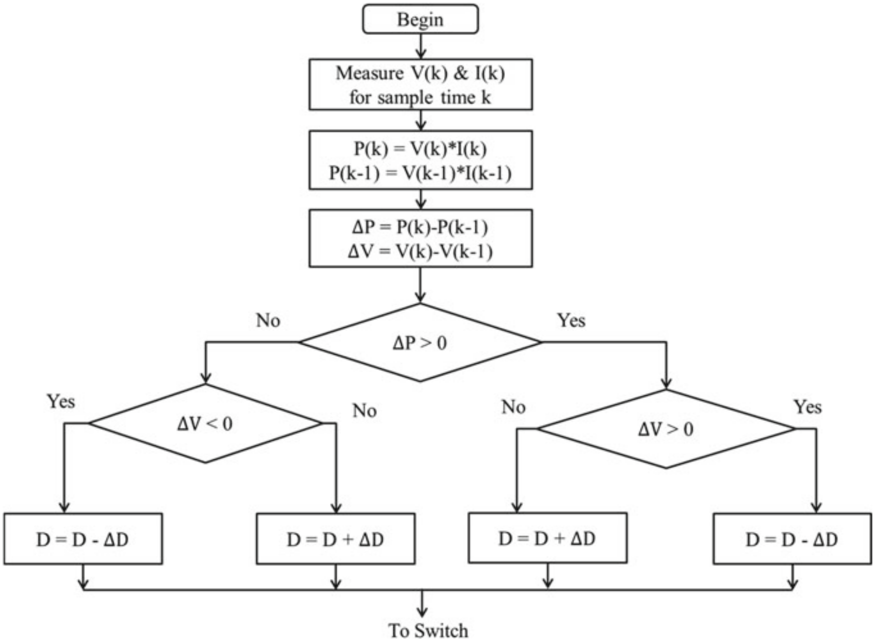

Fig. 6 P&O algorithm-based MPPT technique

The system parameter is perturbed during each sample time of P&O MPPT cycle. This leads to sustained output power oscillation around the MPP region even after attaining the desired operating point. This results in unnecessary power loss and poor conversion efficiency. The power loss will be more predominant in slowly varying environmental conditions. Also, the P&O MPPT algorithm may wrongly track MPP when environmental factors change rapidly.

3.2 Fuzzy Logic MPPT

The typical MPPT approach (P&O) has difficulty tracking MPP in varying environmental conditions and also offers poor conversion efficiency. As a result, the FLC-supported MPPT method is implemented for the photovoltaic (PV) system to have better tracking performance and conversion efficiency under variable environmental circumstances. A typical FLC has four key modules.

Fuzzifier: Converts crisp values into fuzzy input sets.
Fuzzy rules: IF-THEN sentences are employed to define a set of rules for controllers.
Inference: A group of rules are employed to map input to output.
Defuzzifier: Maps output to crisp value.

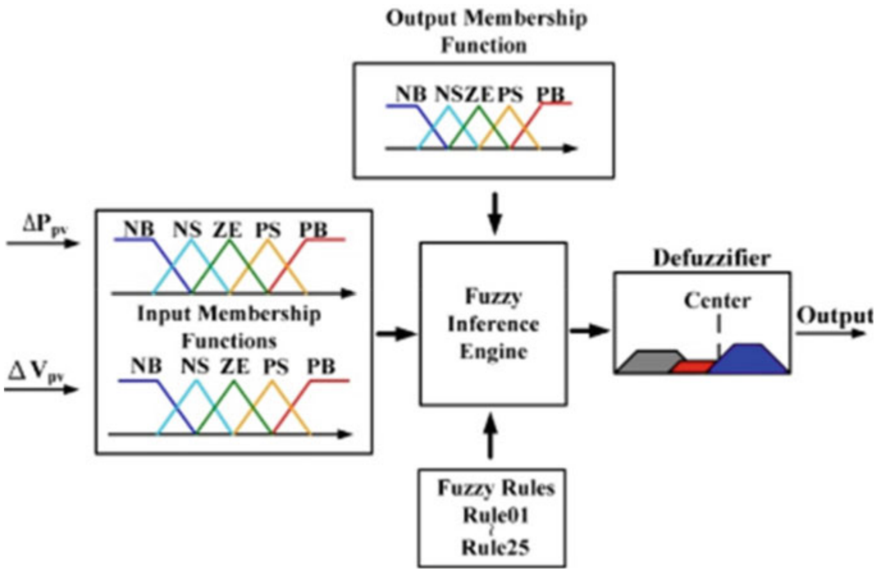

Fig. 7 Components of FLC

FLC components are shown in Fig. 7.

FLC uses different kinds of input and output variables [14]. Here, PV voltage and power are engaged as inputs, while duty cycle (δ) is referred as the output. The choice of PV power and voltage as FLC control variables simplifies design. Equations 3 and 4 define the expression for the input variable.

$$\Delta V_{PV} = V(m) - V(m-1) \quad (3)$$

$$\Delta P_{PV} = P(m) - P(m-1) \quad (4)$$

where ΔP_{PV} and ΔV_{PV} refer to variation in input variables for consecutive sampling intervals. The input variables are continuously sampled at m interval time.

Selection of membership values for input and output variables of FLC has a crucial role to achieve better MPP tracking performance. The mapping of membership function values for ΔP_{PV}, ΔV_{PV} and δ is presented in Fig. 8.

The membership's functions are distributed into five distinctive linguistic variables such as BN, SN, Z, BP and SP, where SN and BN refer to negative small and negative big, respectively; SP and BP point to positive small and positive big, respectively, whereas Z points to Zero. Figure 8 illustrates mapping of linguistic variables. Total of 25 rules are incorporated into the inference system for five linguistic variables. Table 3 presents the complete sets of fuzzy rules. Then, defuzzification is done using the centre of gravity (COG) method. The mathematical expression for COG method is given in (5).

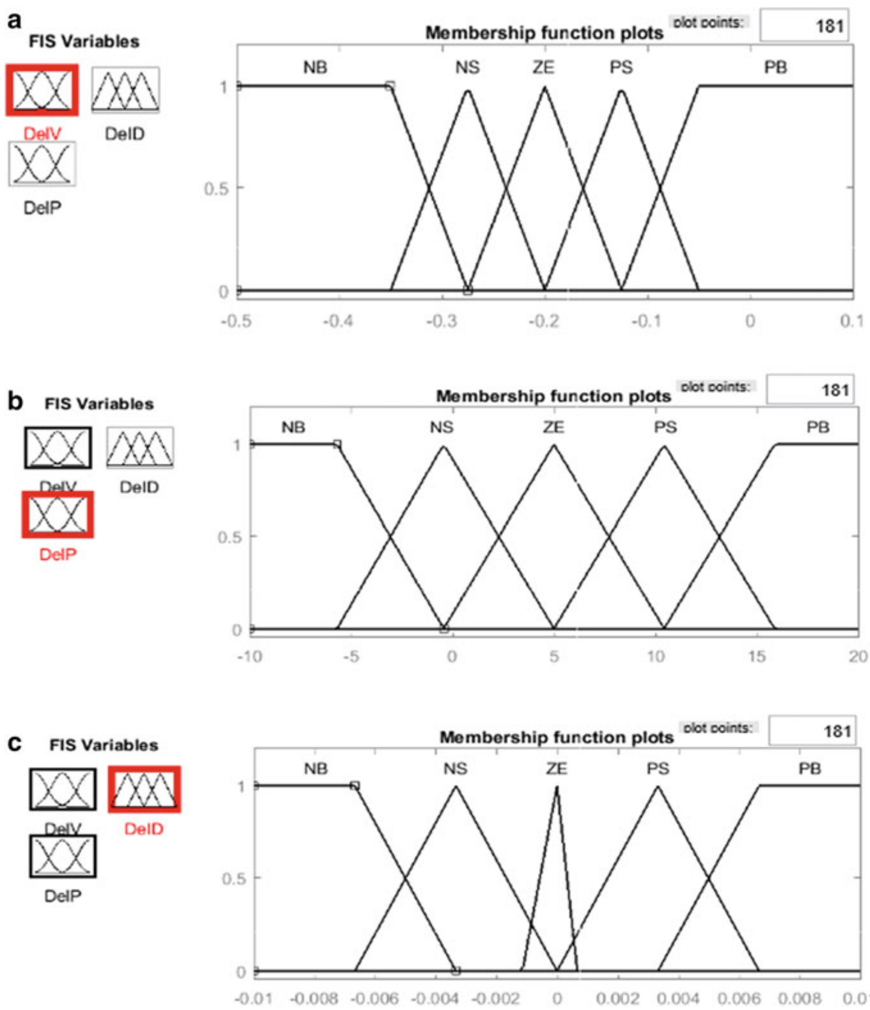

Fig. 8 **a** ΔV_{PV} membership values. **b** ΔP_{PV} membership values. **c** ΔD membership values

$$Y_{\mathrm{COG}} = \frac{\sum_{i=1}^{n} S_i(T_i)T_i}{\sum_{i=1}^{n} S_i(T_i)} \tag{5}$$

where S_i points to the inference result; T_i refers to output.

Table 3 Complete rule base of FLC system

ΔP_{pv}	ΔV_{pv}				
	BN	SN	Z	SP	BP
BN	SP	BP	BN	BN	SN
SN	SP	SP	SN	SN	SN
Z	Z	Z	Z	Z	Z
SP	SN	SN	SP	SP	SP
BP	SN	BN	BP	BP	SP

4 Simulation Outcomes

The simulation is implemented using MATLAB/Simulink software version 2020a by considering the following assumptions:

- DC resistive load is considered for analysis.
- Converter efficiency is considered as 100%.

A 5 kW PV array system modelled to deliver power to DC resistive load via converter (boost) and MPPT controller. The simulation model for the overall system is presented in Fig. 9. Also, a Simulink model for FLC MPPT method is displayed in Fig. 10. PV system performance with P&O and FLC MPPT approaches is evaluated at various solar irradiance (Ir) and temperature (T) levels. Figures 11 and 12 depict variations in solar irradiance and temperature, respectively. The simulation lasts for two seconds.

4.1 *P&O Algorithm*

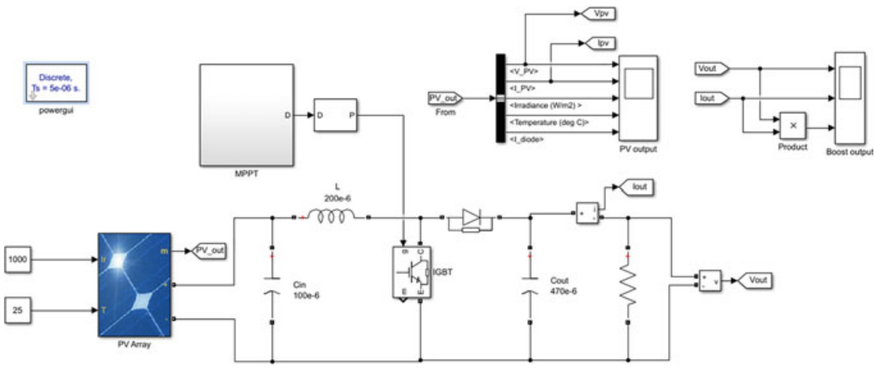

Fig. 9 Overall PV system Simulink model

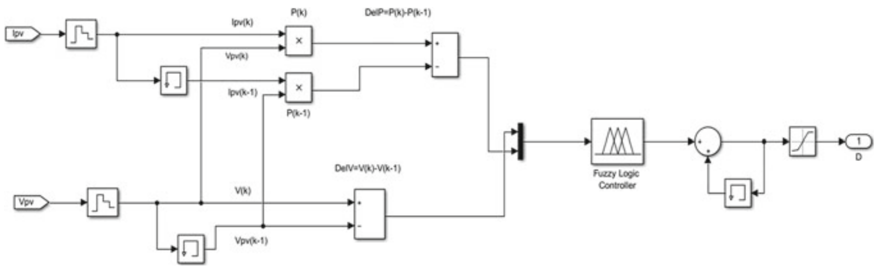

Fig. 10 FLC MPPT Simulink model

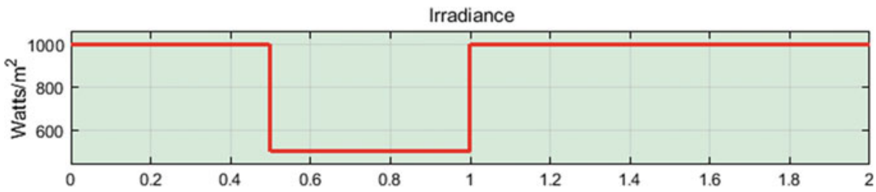

Fig. 11 Solar irradiance variation

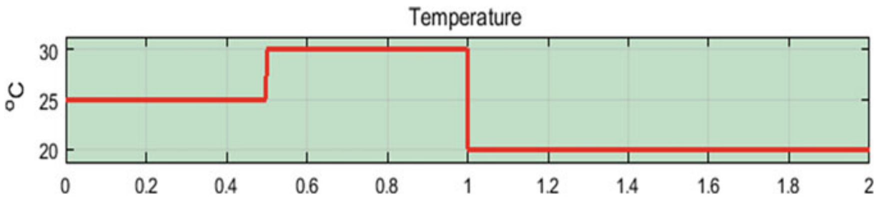

Fig. 12 Temperature variation

Case 1: Variable Irradiance but Constant Temperature (25 °C) Initially, the sun irradiation is held constant at 1000 W/m^2 between 0 and 0.5 s. However, at time t = 0.5 s, the radiation level is lowered to 500 W/m^2 and remains constant until time t = 1 s. Then, at time t = 1 s, solar irradiance is once again raised to 1000 W/m^2. Figure 13 illustrates simulation results for PV systems with P&O MPPT controller for changing irradiance conditions. From Fig. 13, it was evident that the P&O MPPT controller somehow tracks the MPP but produces a sustained oscillation in PV output power.

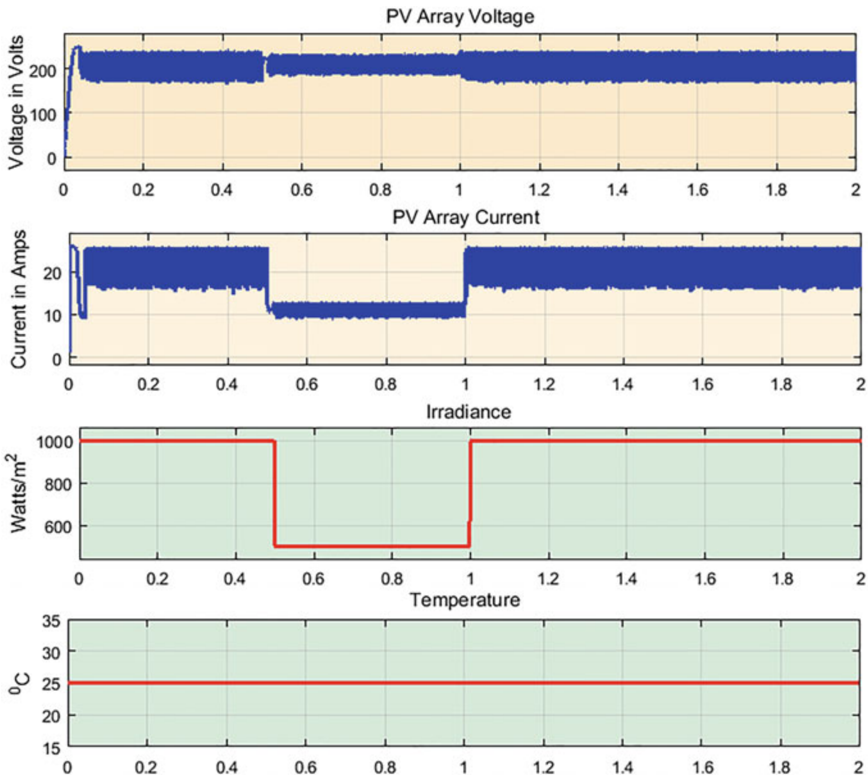

Fig. 13 PV output with P&O MPPT under variable irradiance

Case 2: Variable Temperature but Constant Irradiance (1000 W/m^2) For this case, the initial temperature of the solar cell is assumed as 25 °C for a time interval 0–0.5 s. Then, at time $t = 0.5$ s the temperature is raised to 30 °C and is maintained till $t = 1$ s. At time $t = 1$ s, it falls to 20 °C and the same is maintained till $t = 2$ s. Figure 14 depicts the simulation test result of the P&O MPPT controller for variable temperature. Here also, a sustained power oscillation took place around the MPP region. Therefore, referring to Figs. 13 and 14, it was witnessed that there was a sustained power oscillation around MPP when using the P&O MPPT controller. As a result, unnecessary power losses were experienced in the PV system.

4.2 FLC MPPT

Case 1: Variable Irradiance but Constant Temperature (25 °C) PV system output for a FLC MPPT technique under different irradiance is presented in Fig. 15. It was obvious from Fig. 15 that FLC MPPT technique effectively tracks down the MPP

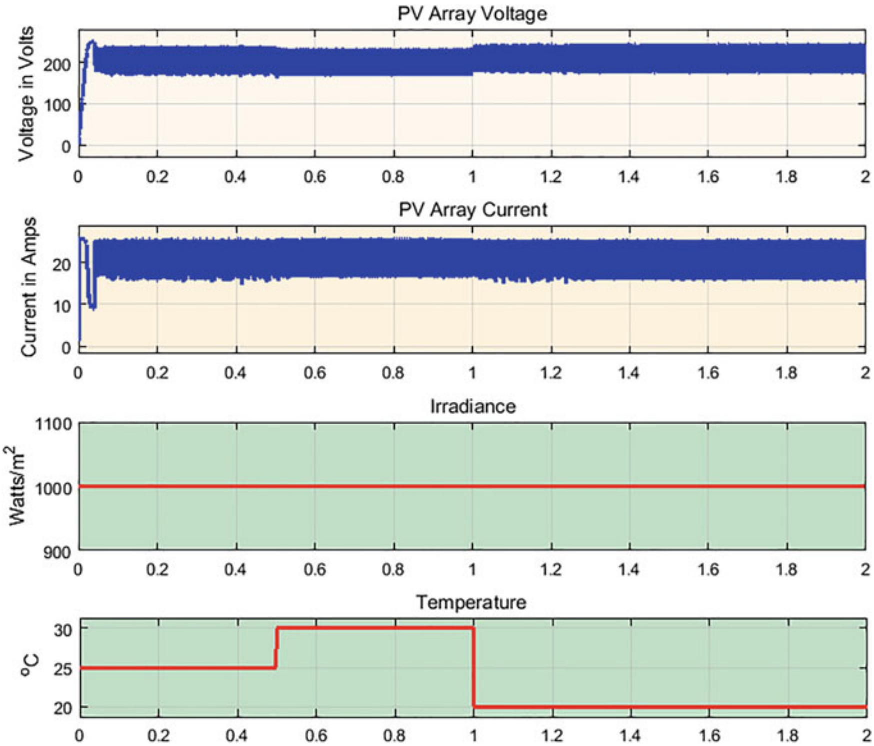

Fig. 14 PV output with P&O MPPT under variable temperature

irrespective of solar irradiance variation. Furthermore, compared to P&O MPPT controllers, power oscillation around the MPP zone is greatly decreased.

Case 2: Variable Temperature but Constant Irradiance (1000 W/m^2) Figure 16 illustrates the simulation test result of PV system for FLC MPPT controller for variable temperature. Here also, power oscillations are reduced with FLC MPPT technique but not as much referred to as case 1 condition. The simulation results reported above demonstrated that the FLC-based MPPT approach outperforms the P&O MPPT controller in terms of outcomes and response under varied conditions. In addition to this, FLC MPPT technique registers minimum power losses at steady state. Table 4 summarizes the results of the P&O and FLC MPPT approaches for various sun irradiance and temperature conditions.

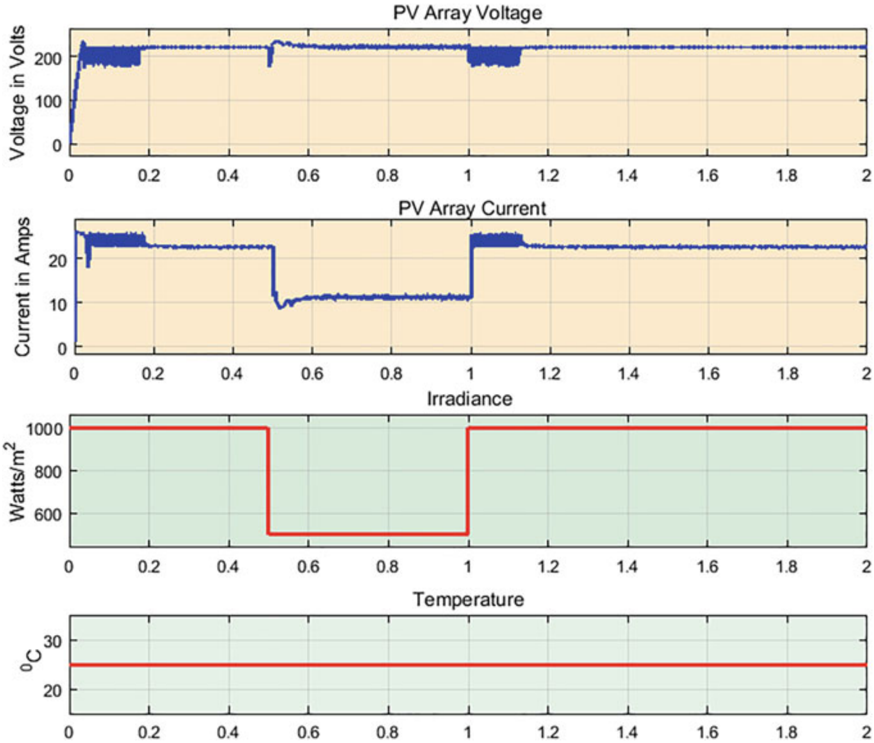

Fig. 15 PV output with FLC MPPT under variable irradiance

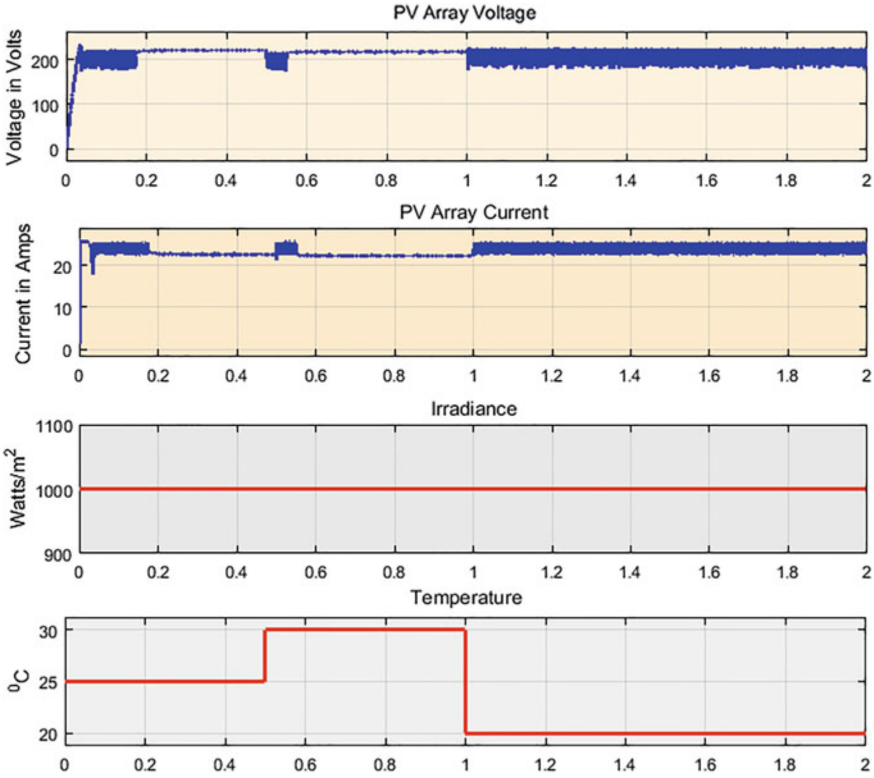

Fig. 16 PV output with FLC MPPT under variable temperature

Table 4 PV output under different solar irradiance and temperature

Variable	MPP parameters					
	P&O MPPT			FLC MPPT		
	V_{pv} (V)	I_{pv} (A)	P_{pv} (W)	V_{pv} (V)	I_{pv} (A)	P_{pv} (W)
Ir (W/m^2)	**Different solar irradiance**					
1000	213.1	21.8	4585	221.2	22.62	5003
500	210.1	11.76	2458	222.6	11.14	2480
T (°C)	**Different temperature**					
25	213.1	21.8	4585	221.2	22.62	5003
30	212.3	20.4	4331	220.4	22.54	4968
20	210.2	20.1	4225	222.1	22.60	5019

5 Conclusion

The simulation performance of the FLC MPPT technique is investigated in this research for a 5 kW distributed photovoltaic system under fluctuating solar radiation and temperatures. The suggested PV DG system model is implemented in the MATLAB/Simulink 2020a software platform. The simulation test results of FLC and P&O MPPT techniques were related to each other. For a changing operating condition, the P&O MPPT method produced sustained power oscillation around the MPP region. But, FLC MPPT controller has significantly reduced the steady-state oscillation with better tracking response compared to P&O technique. FLC offers simpler design and it does not need knowledge about the system model. Also, inclusion of variable step size in the control variable of FLC provided improved results than P&O technique.

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