IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

Journal Européen des Systèmes Automatisés
Vol. 59, No. 4, April, 2026, pp. 1019-1027
Journal homepage: http://iieta.org/journals/jesa

Maximizing Boost Converter Efficiency: An Analytical Comparison Between Perturb and Observe and Fuzzy Logic Strategies

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https://doi.org/10.18280/jesa.590413

Received: 10 January 2026
Revised: 12 March 2026
Accepted: 6 April 2026
Available online: 30 April 2026

Keywords:
solar system, boost converter, maximum power point tracking, fuzzy logic system, Perturb and Observe algorithm

ABSTRACT

Boost converters play an important role in energy systems, such as solar systems, where losses must be kept to a minimum due to efficiency concerns. This study compares the efficiency of boost converters using two control strategies: the fundamental forms of learning, the Perturb and Observe (P&O) algorithm as well as the Fuzzy Logic Control (FLC). Although every study must be compared with the traditional way, P&O. FLC provides flexibility. Performance comparison of each technique was tested by using simulation and methods for different at constant loads and different input voltage levels. Normative data show that while P&O performance appears satisfactory, FLC significantly improves effectiveness, particularly under varying voltage, which suggests the FLC's capability to advance power electronic techniques.

1. INTRODUCTION

Solar power is one of the most common ways to obtain energy these days. People are getting more and more worried about using clean, renewable energy sources and keeping the environment safe. Photovoltaic (PV) systems, which turn sunlight into electricity, have been at the forefront of the push for green energy. One of the hardest things about PV systems is figuring out how to achieve high conversion efficiency and keep it that way even when the amount of sunlight and other environmental factors change [1].

To get around these problems, advanced control techniques and power electronic interfaces are used. The boost converter is a DC-to-DC converter circuit that raises the voltage of solar panels to the best level. It is one of the most important things in this area. To get the maximum power point tracking (MPPT), which is the most power that can be taken from the PV panels, the boost converter needs to be controlled perfectly [2].

The common ways to get, MPPT, to work are by using the Perturb and Observe (P&O) algorithm and the Fuzzy Logic Control (FLC) methodology. So, the P&O algorithm is more popular because it is simple to use and does not need complicated math to work. MPPT is what this is about [3]. On the other hand, MPPT using FLC is different. FLC use logic to understand how the system works because MPPT systems can be unpredictable and have many variables like those found in solar power systems. MPPT is important here [4].

Analyzing data that has some errors, FLCs use some common-sense rules to make control more flexible and tolerant compared to the method. This article compares the P&O algorithm and FLC for solar boost converters in the analysis and control domain [5]. The P&O algorithm and FLC are discussed in detail, including their principles and advantages and disadvantages, especially how efficient and steady they are for PV systems. By comparing these methods, we want to show that future control strategies like using logic can improve how solar energy systems work and make harnessing solar power more reliable. The goal is to make solar power systems better and more dependable by using control methods, like fuzzy logic [6].

2. LITERATURE REVIEW

Boost converters are used in PV systems because they help get the power from the solar arrays. To do this, people usually use two methods: the P&O method and FLC. Recently, people have been trying to combine these methods to make the boost converters work better. Some old studies show that using FLC with the P&O method can make the system more stable and get power out, especially when things are not working normally. Boost converters are important in these systems because they help make the most power from the solar arrays. The P&O method and FLC are used together to improve the boost converter efficiency [7].

Mahdi et al. [8] worked with him found out that a special kind of controller that works in parallel and can adapt to things, which combines P&O and fuzzy logic and ANFIS makes things work a lot better when things are changing all the time.

Brahmi et al. investigated adaptive P&O-fuzzy control. This method made it possible for the system to respond quickly and keep track of energy use effectively since the P&O method is simple and fuzzy logic is flexible [9].

Fatima-Zahra et al. [10] examine the MPPT techniques P&O, FLC, and ANN across different temperature scenarios.

The results show that FLC and ANN are more accurate and respond faster than P&O, especially when the temperature changes.

Raj and Joshua [11] noted that fuzzy logic has demonstrated superior performance in managing the nonlinear attributes of the PV module, outperforming the P&O and incremental algorithms in precise power tracking.

3. SIMPLIFIED MODEL OF A PHOTOVOLTAIC CELL

Solar cells or PV cells are the basic units of PV systems, wherein light is converted directly into electricity. The latter can be described with the help of an equivalent circuit, which is depicted in Figure 1. The modeling of a PV cell is very essential for the analysis and improvement of solar power system performance [12]. A schematic diagram of a PV cell can show it as an electrical circuit with a current source (I_{ph}), a diode, and series resistance (R_s) and parallel resistance (R_{sh}). The present source concerning the photon-generated current is notable, as it illustrates the current in relation to solar irradiance [13].

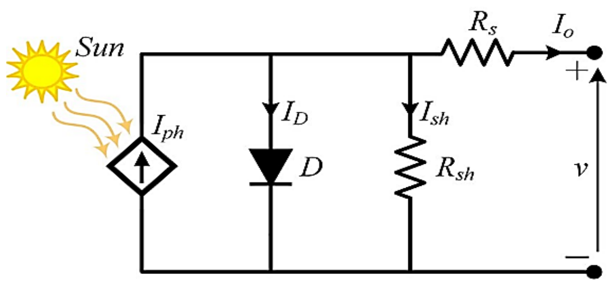


Figure 1. Solar cell equivalent circuit

The output current (I) from the PV cell can be expressed as:

$$I = I_{ph} - I_D\left(q^{\frac{V+IR_s}{nV_t}} - 1\right) - (V - IR_s)/R_{sh} \tag{1}$$

where, V refers to the cell voltage, V_t is the thermal voltage, n refers to the ideality factor, I_D refers to the diode current and R_{sh} refers to the shunt current [14].

For ideal conditions, assuming negligible series resistance and infinite shunt resistance, this equation simplifies to:

$$I = I_{ph} - I_0\left(e^{\frac{V}{nV_t}}\right) - 1 \tag{2}$$

This model, which aims at capturing the basic form of PV cell performance, is therefore useful in the analysis of the performance of the PV cells under different conditions [15].

4. BOOST CONVERTER

A boost converter is specifically a DC-DC power converter that has the ability to increase voltage at the load as it is compared to the supply voltage. This device functions in a manner that energy is stored in an inductor and then released at a higher voltage. When in use, a switch, usually in the form of a transistor, opens or closes to alternate in controlling the flow of energy [16]. When the switch is ON, the inductor draws current from the input supply and can store this energy as a magnetic field. When the switch is off, the magnetic induction releases this stored energy to augment the output with the input supply to give a better voltage output. A diode allows current to flow in a specific direction only, and a capacitor is responsible for maintaining output voltage ripple. Figure 2 represents the circuit diagram of the boost converter [17].

Because the output boost converter voltage is always greater than the supply voltage, it is most commonly utilized in applications that include battery-operated devices, power supply management, and renewable energy systems in electronic circuits. Due to flexibility, small dimensions, and capacity of stable voltage, it is used as an element in actual power electronics [18]. The relationship of the input-output voltage of the boost converter is stated by:

$$V_o = \frac{V_{in}}{(1-\alpha)} \tag{3}$$

where, V_{in} refers to the voltage source voltage, V_o refers to the load voltage and α refers to the duty cycle of the switching device [19].

The boost design calculation:

Let: I= irradiance (1000 W/m^2)

f_S = switching frequency (25 kHz)

V_{in} = input boost voltage (20 V)

D = duty cycle (0.5)

Δ_{IL} = change in inductive current (2 A)

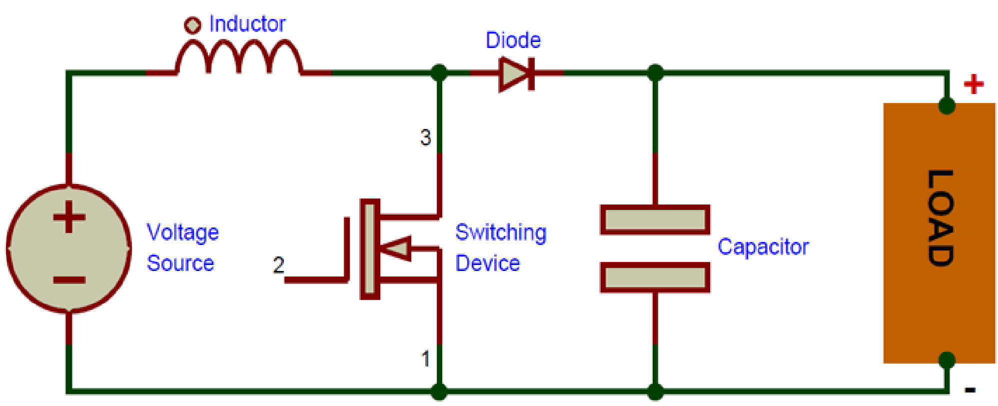


Figure 2. Boost converter

$$1.\ L = \frac{Vin\ .\ D}{fs\ .\ \Delta_{IL}} = \frac{20 \times 0.5}{25000 \times 2} = 200\ \mu H$$

$$2.\ C_1 = \frac{\Delta_{IL}}{8.\ f_s\ .\ \Delta V_{in}} = \frac{2}{8 \times 2500 \times 0.0625} = 200\ \mu F$$

Output capacitor:

$$3.\ C = \frac{I_{out}\ .\ D}{f_s\ .\ \Delta V_{out}} = \frac{2.3 \times 0.5}{25000 \times 0.1} = 230\ \mu F$$

5. MAXIMUM POWER POINT TRACKING TECHNIQUE

When we talk about PV systems MPPT is really important for getting the results. Several algorithms have been made for this. There are two ways to do this the P&O algorithm and the FLC-based MPPT. The P&O method works by changing the operating voltage and seeing if the power increases. If the power increases, it keeps doing what it is doing. If not, it changes. This way is used a lot because it is simple. However, it has a problem [20]. It cannot handle changes in the environment very well and can keep going back and forth around the point where it gets the most power. On the hand fuzzy logic-based MPPT uses special controllers to deal with the complicated and changing characteristics of PV systems. This method uses words and rules to find the operating point no matter what the conditions are. It is better than methods because it responds faster and changes more smoothly when the sun's rays and temperature affect power generation. This helps to minimize power losses [21].

By combining the things about P&O and fuzzy logic these MPPT techniques make solar energy systems much better. MPPT techniques are very useful, for PV systems. MPPT helps PV systems to work at their best [22].

5.1 Perturb and Observe Maximum Power Point Tracker technique

The P&O scheme MPPT is the most popular technique for PV systems because of its simplicity and efficiency. This technique works in the process of pulsing the voltage or current of the PV system and analyzing the impact on the output power. In the latter case, if the perturbation increases the power of the system, the change goes in the same direction; if it decreases, the change turns in the opposite direction [23]. This periodic process assists the system in being close to the Maximum Power Point (MPP) as the PV module input/output characteristics plot. However, the P&O method is easier to implement in practice; the convergence curve may oscillate around MPP, and the P&O method has a low performance under dynamic environments such as rapid changes in sunlight and temperature. However, its simplicity, low cost, and reasonable accuracy make P&O a preferred choice for MPPT in many solar energy applications. The flow chart of the P&O method is given in Figure 3 below [24].

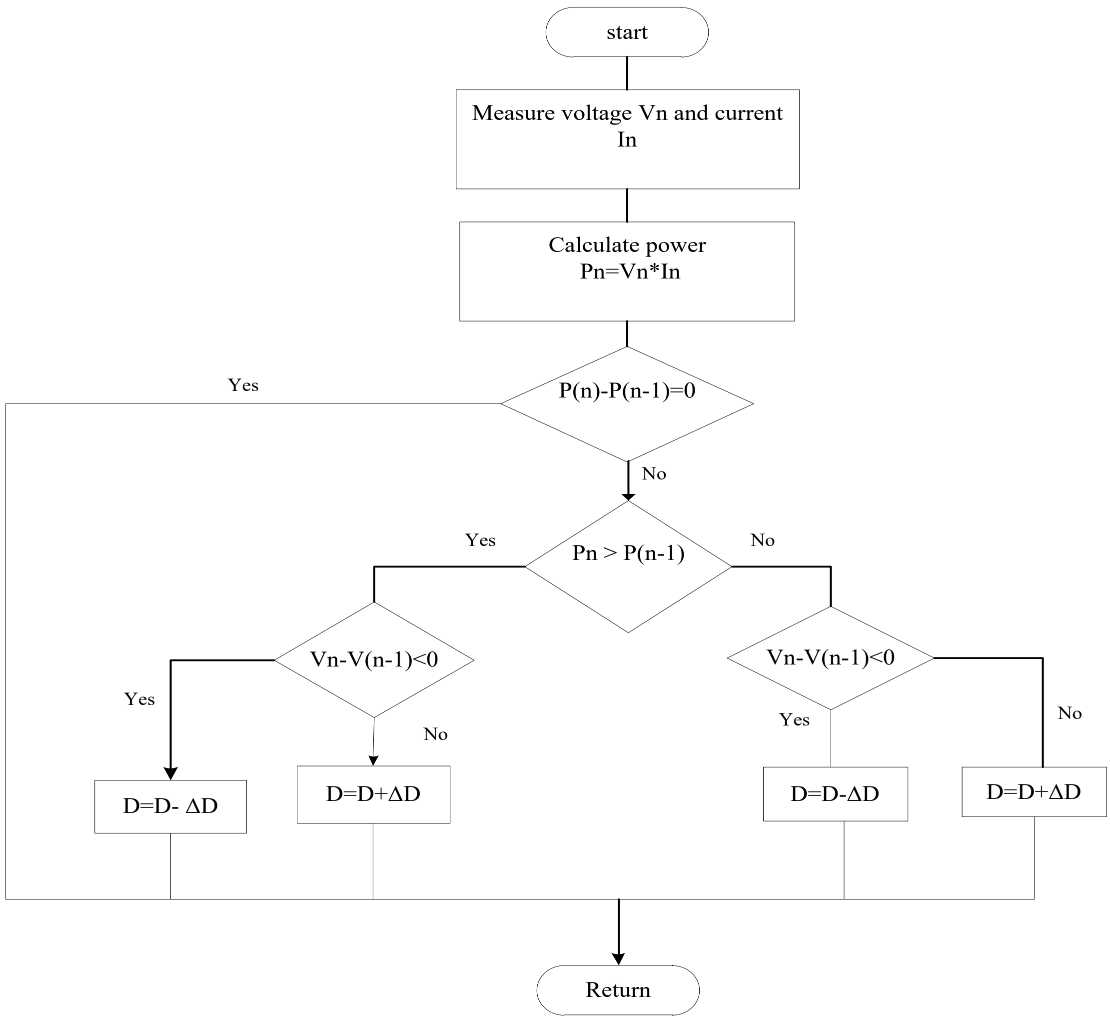


Figure 3. Perturb and Observe (P&O) flowchart

5.2 Fuzzy logic-based maximum power point tracking technique

Fuzzy logic-based MPPT is one of the direct control techniques used in PV systems to control energy losses under fluctuating weather conditions. Fuzzy logic MPPT is different from other methods due to the use of an FLC, which is effective in the control of nonlinear sources such as PV systems. This controller employs a set of linguistic rules as well as membership functions in order to manipulate input variables such as change in voltage or current [25]. Thus, by such input evaluations, the fuzzy logic system can adapt the operating point of the PV system for the most effective output. This approach has some benefits, such as increased speed of response, lower fluctuations around the MPP, and a harvested energy comparison under fluctuating irradiation and temperature values. Therefore, fuzzy logic-based MPPT improves the general reliability and energy output of the solar power systems, which makes it an important method in the augmentation of renewable energy systems [26].

5.3 Fuzzy Logic Control construction

Human language can be used as an example of fuzzy logic. A linguistic variable is redirected to an automatic control approach by an FLC. A knowledge database is used to create fuzzy logic rules. As shown in Figure 4, set error (e) and change of error (Δe) as the FLC's input variables. Output 1 is the controller's output variable.

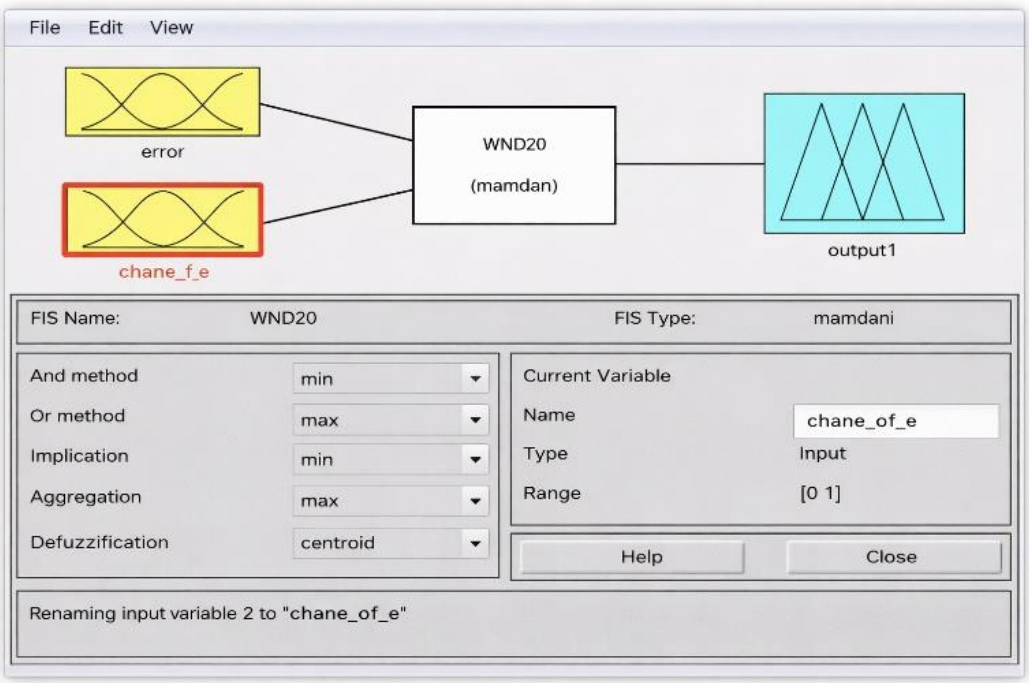
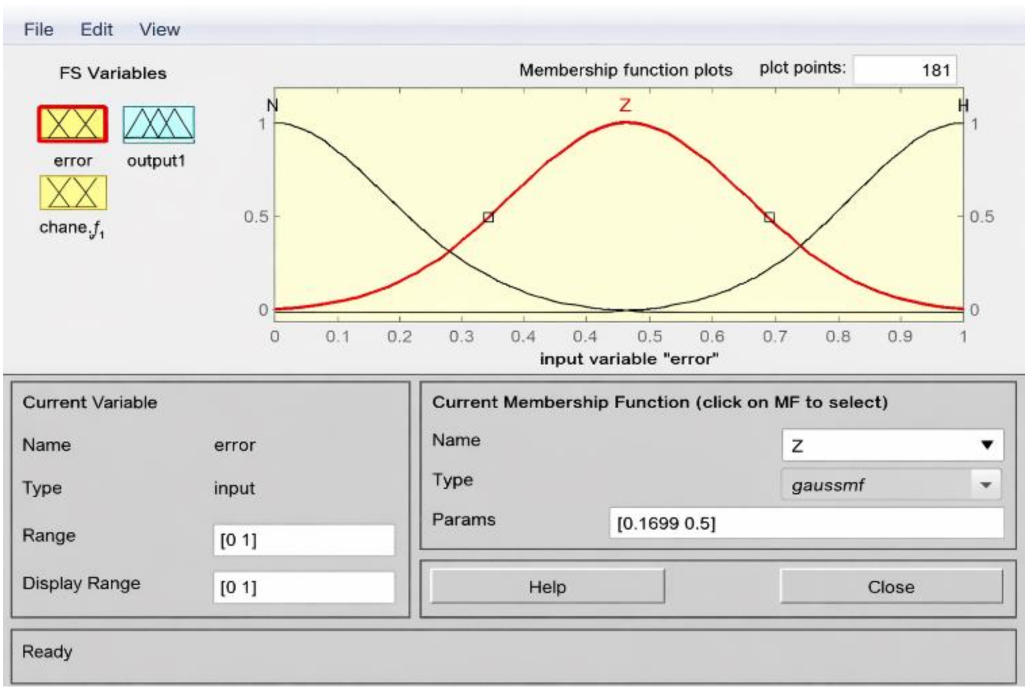
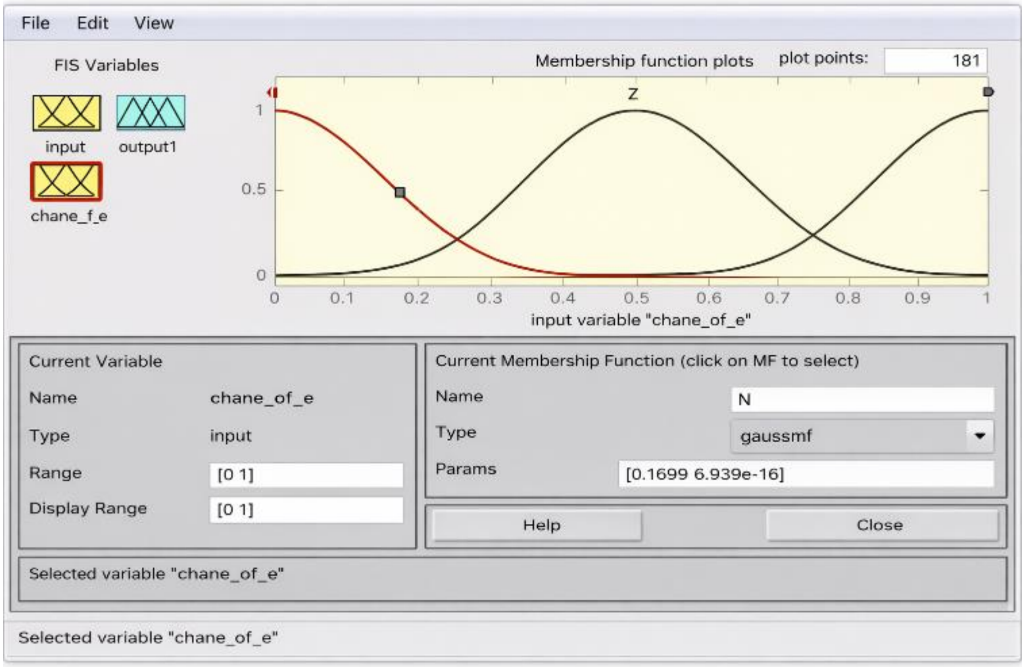


Figure 4. Internal construction of Fuzzy Logic Control (FLC)



(a) error (e)



(b) change of error (Δe)

Figure 5. Input variables of Fuzzy Logic Control (FLC)

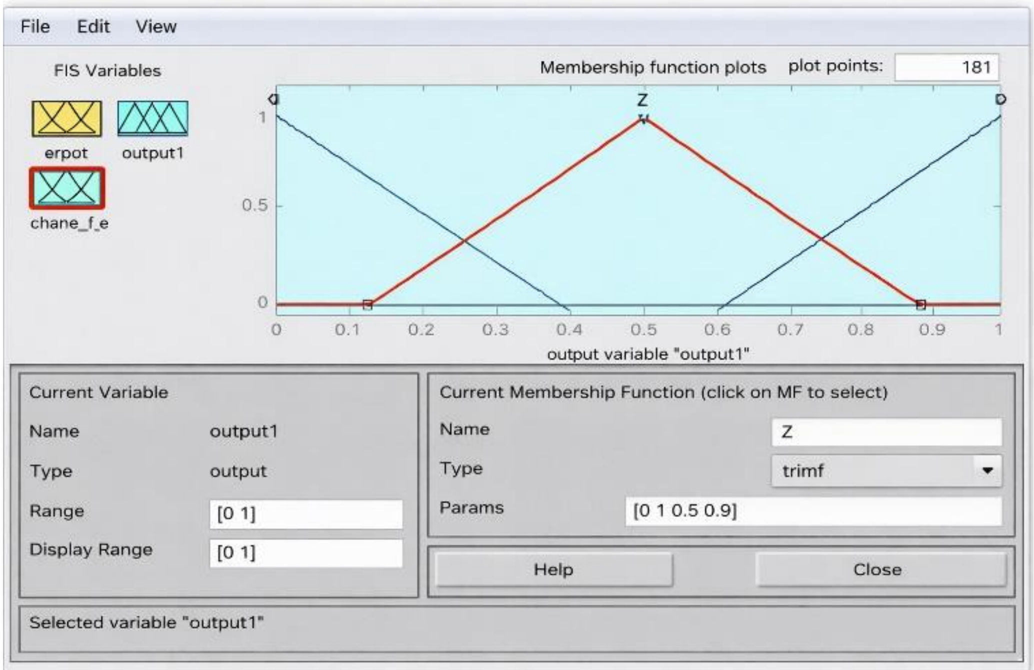


Figure 6. Output variable of Fuzzy Logic Control (FLC)

The linguistic variables are:
NB: negative big
NS: negative small
Z: zero
PS: positive small
PB: positive big

The input variables of FLC are selected as gauss waveform in order to coverage all points in the domains as shown in Figure 5.

The output variable is selected as trams waveform in order to keep the output signal lies within linear region as shown in Figure 6.

The dimensions of fuzzy rules matrix are [5 × 5] which is shown in Table 1.

Table 1. Fuzzy logic algorithm rolls that used in this work

		Delta Error						
		NL	NM	NS	ZE	PS	PM	PL
	NL	NL	NL	NL	NL	NM	NS	ZE
	NM	NL	NL	NL	NM	NS	ZE	PS
	NS	NL	NL	NM	NS	ZE	PS	PM
Error	ZE	NL	NM	NS	ZE	PS	PM	PL
	PS	NM	NS	ZE	PS	PM	PL	PL
	PM	NS	ZE	PS	PM	PL	PL	PL
	PL	ZE	PS	PM	PL	PL	PL	PL

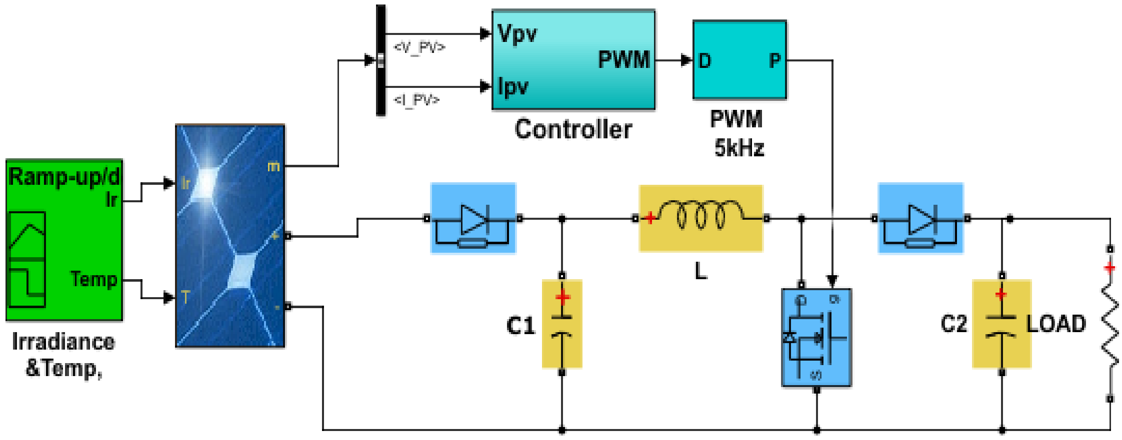


Figure 7. Simulation circuit

6. RESULTS AND DISCUSSION

Figure 7 represents the simulation model of the solar module used in this work using MATLAB/Simulink.

Table 2 is the (Apollo solar energy ASEC-200G6M68) solar module with 1 string in parallel and 2 Series-connected modules per string.

Table 2. Solar module parameters

Apollo Solar Energy ASEC-200G6M68, Parallel Strings 1 and Series String 2	
Maximum Power (W)	200.0217
Open circuit voltage Voc (V)	29.95
Voltage at maximum power point Vmp (V)	24.07
Short-circuit current Isc (A)	8.65
Current at maximum power point Imp (A)	8.31

The boost converter used in this system has the following parameters, as shown in Table 3.

Table 3. Boost converter parameters

Input capacitor C1 (F)	200e-6
Inductor L (H)	200e-6
Output capacitor C2 (F)	230e-6

Figure 8 shows the input irradiance to the PV array for P&O method and FLC algorithm. The temperature is assuming fixed at 25 °C.

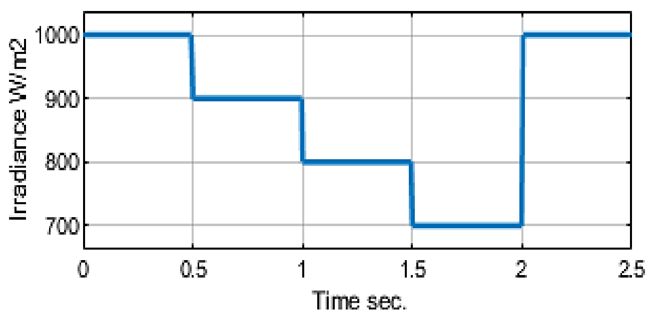


Figure 8. The input irradiance W/m^2

Figure 9 shows the boost voltage, current and power with using the P&O algorithm, respectively.

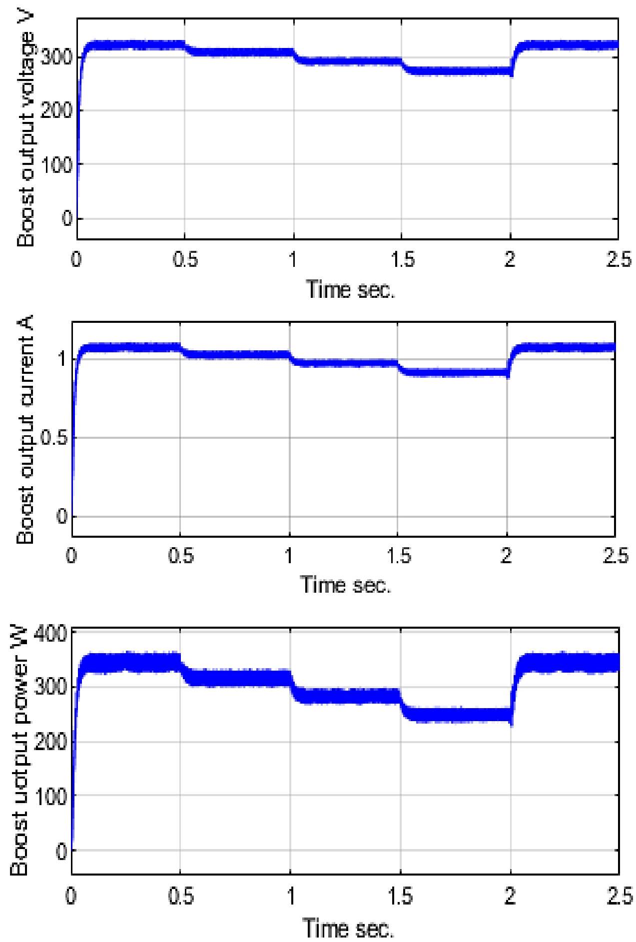


Figure 9. The boost voltage, current and power-based Perturb and Observe (P&O)

Figure 10 represents the boost voltage, current and power with using the FLC algorithm respectively.

Figure 11 illustrates the boost output power, (a) for P&O and (b) for FLC respectively, at simulation time between (0 to 0.5) sec. The power in FLC is more efficient as compared with P&O.

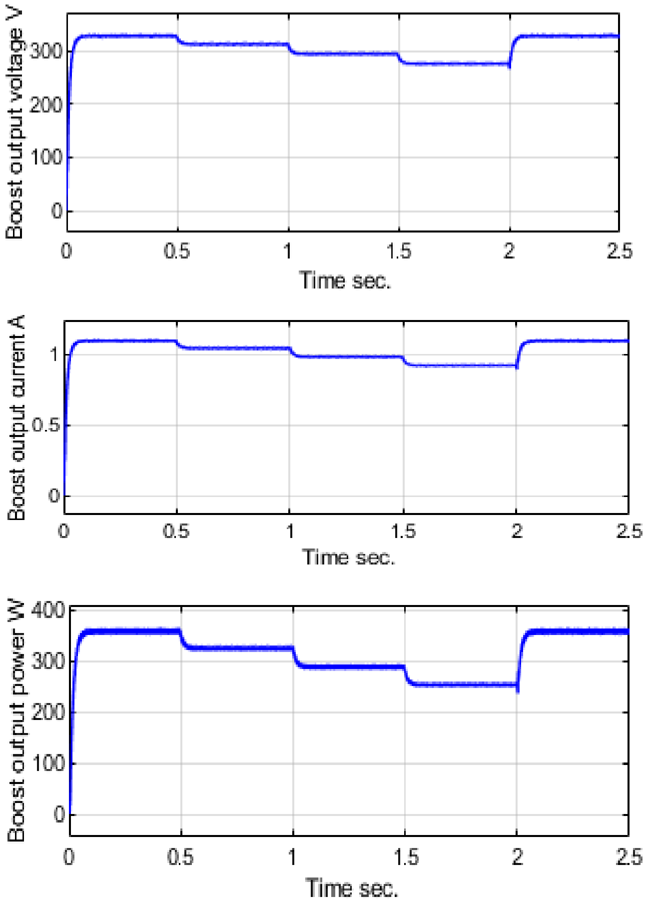
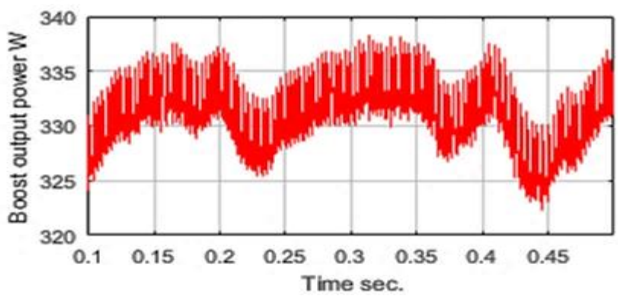
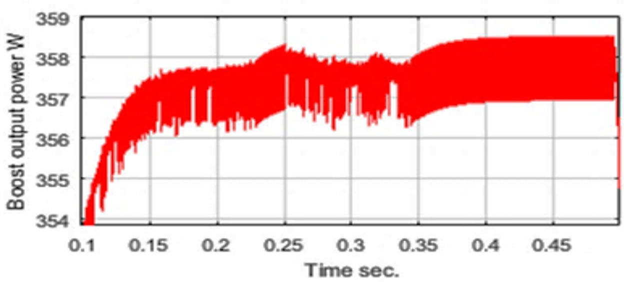


Figure 10. The boost voltage, current and power based Fuzzy Logic Control (FLC)



(a) Perturb and Observe (P&O)



(b) Fuzzy Logic Control (FLC)

Figure 11. Boost power

Once the circuit analysis was completed, a comparative study was conducted and the results are listed in Table 4.

Table 5 represents the rise time, overshoot voltage, settling time and the peak voltage for each control method.

From the dynamic response of the Boost Converter in Table 5, the results we can see that there are several areas in which FLC is better than P&O. The analysis of FLC showed that it takes shorter time of rise time (0.0368 ms) than P&O, which takes 0.0405 ms to respond to changes in voltage. Moreover, the FLC has comparatively a small overshoot of 0.0306 V while the P&O had a substantially large overshoot of 0.3207 V, meaning that FLC has better control over dynamic voltage and offers minimal fluctuation. While comparing FLC and P&O, FLC had slightly higher settling time of 0.0736 ms compared with 0.0405 ms of P&O controller but a short settling time is an extra benefit. Concerning the maximum peak voltage, it was observed that FLC offered the highest value of 267. 49 V as compared with P&O with a value of 259.82 V, which means that FLC is more effective in evaluating the MPP.

Table 4. Comparative analysis for Maximum Power Point Tracker (MPPT) algorithms

Performance Metric	Perturb and Observe (P&O) Algorithm (Conventional)	Fuzzy Logic Controller (Proposed)
Tracking Speed (rise time)	Moderate	Fast/Rapid
Steady-state Oscillation	High (continuous ripples)	Negligible/Smooth
Settling Time t_s	About 0.15 sec.	About 0.12 sec.
Tracking Accuracy	Moderate	High/Precise
Efficiency at 1000W/m²	About 87.5% (Average)	About 91.5% (Stable)
Efficiency at 200W/m²	About 72% (Reduced)	About 88% (Robust)
Complexity of Implementation	Low	Moderate
Reliability under Rapid changes	Low	High

Table 5. The comparison results for the boost voltages

MPPT Method	Rise Time ms	Overshoot V	Settling Time ms	Peak Voltage V
P&O	0.0405	0.3207	0.0736	259.82
FLC	0.0368	0.0306	0.0405	267.49

Note: MPPT = Maximum Power Point Tracker; P&O = Perturb and Observe; FLC = Fuzzy Logic Control

7. CONCLUSIONS

The operations associated with the control of environmental factors such as temperature and solar radiation can be better regulated in terms of precision and flexibility because the logical rules at work do not create rigid control points and jerky responses that can disrupt system stability and erode energy efficiency. Its design and tuning are meticulous, which also escalates the question of programming and implementation of algorithms, but yields high results, especially in constantly shifting environments because it enhances the efficiency of energy acquisition. However, it can be less efficient, having higher complexities, which need additional computational resources, hence higher cost and energy consumption. Unlike the P&O method, the design and implementation of fuzzy logic require the repetitive usage of simple algorithms to adjust the operating point to attain maximum power. However, it may cause oscillations around the maximum power point (MPP), thus making the efficiency of the system low. If it does not immediately respond to changes in the environment, this will lead to losses. It performs satisfactorily when there are no changes in the environment, while it has poor performance when compared to fuzzy logic in cases of changing environments.

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