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PERFORMANCE ANALYSIS OF VARIOUS TYPES OF DC-DC CONVERTERS FOR ISOLATED PV SYSTEM WITH FLC BASED INCREMENTAL CONDUCTANCE MPPT CONTROLLER.

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Abstract: This paper integrates a Fuzzy Logic approach with the Incremental Conductance algorithm. The integration of photovoltaic (PV) systems into power generation has grown significantly due to the increasing demand for renewable energy. Changes in solar irradiations cause variations in voltage which in turn affect PV output power. To combat this situation, it is desired for PV system equipped with a fast-converging maximum power point tracking (MPPT) system. The MPPT System need to be aligned with the operational features of the Power electronic converter as the converter needs to adjust its duty cycle in real-time using the feedback signal from the MPPT system. This ensures that the PV system operates efficiently, even when irradiance and temperature conditions change. The Incremental Conductance (INC) algorithm is a widely used method for Maximum Power Point Tracking (MPPT). However, it has limitations such as possibility of struck to a local Maximum Power Point (MPP) instead of accurately converging to the single global MPP also it may respond slowly for the rapid changes in environmental conditions. To address these issues, this paper integrates a Fuzzy Logic Controller (FLC) with the INC algorithm. The combination of FLC and INC enables the solution to reach the global MPP by avoiding local MPP. This proposed method has improved the tracking efficiency in terms of power output The performance of this FLC-based INC MPPT controller is evaluated across different DC-DC converters, such as boost, Cuk, and SEPIC in an isolated PV system. This paper analyses and compares the tracking performance of these converters using the fuzzy logic-based INC MPPT method.
KEY WORDS- PV System, Maximum power point Tracking (MPPT), Maximum Power Poin t(MPP), Fuzzy Logic Controller (FLC), Incremental Conductance (INC), Boost Converter, Cuk Converter, SEPIC Converter.

I INTRODUCTION

Photovoltaic (PV) systems are increasingly integrated into global power grids and play a significant role in electricity generation. Improving the efficiency of these systems is essential to meet growing energy demands and support the transition to sustainable energy sources. PV cells convert solar energy into electrical energy, but their performance is influenced by environmental factors such as temperature and solar irradiance. To optimize the performance of PV systems, it is necessary to maintain maximum power output under varying conditions, which is achieved through Maximum Power Point Tracking (MPPT). The primary function of an MPPT controller is to extract the maximum power from PV arrays despite fluctuations in environmental conditions. By ensuring PV modules operate at their Maximum Power Point (MPP), MPPT reduces the cost per watt and enhances the reliability of the system. MPPT algorithms calculate the power of the PV array using voltage and current measurements and adjust the duty cycle of the converter to achieve optimal performance. These algorithms vary in terms of complexity, cost, and efficiency but are critical for minimizing power losses and maximizing energy output under changing conditions. [1][6].
Fuzzy Logic Control (FLC) and Artificial Neural Networks are extensively utilized for MPPT due to their robustness, accuracy, and speed. Optimization techniques such as Genetic Algorithm (GA), Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) are also employed to enhance MPPT accuracy. These methods improve tracking speed, steady-state performance, and reduce

tracking costs. Each algorithm, however, has its own set of advantages and disadvantages. The Perturb and Observe (P&O) method is one of the commonly used algorithms, appreciated for its simplicity and the lack of necessity to know the solar cell's characteristic curve in advance. Nonetheless, it lacks precision in steady-state MPPT. The P&O method continuously compares two points, even when near the MPP, leading to oscillations and power losses. Moreover, it is prone to misjudgements [10]. To address these issues, the Hill-Climbing and Incremental Conductance (INC) methods have been developed as improvements to the P&O method. The Hill-Climbing method adjusts the duty cycle of the converter's switch by using the slope of the power-versus-voltage curve as the judgment equation, ensuring the slope becomes zero at the MPP [7]. The INC method, derived from Hill-Climbing, uses the slope of the voltage-versus-current curve for decision-making. However, both methods use a fixed step size for adjusting the duty cycle, resulting in persistent oscillations [6]. This paper introduces a hybrid MPPT technique that combines Fuzzy Logic Control with the Incremental Conductance algorithm. The slope and slope variation of the power-versus-voltage curve are utilized as input variables for the fuzzy logic controller. The effectiveness of this approach depends on well-designed membership functions, which require extensive experimentation and adjustments. Poorly constructed memberships necessitate modifications to the fuzzy rules for achieving optimal tracking speed and stability. The hybrid MPPT controller improves steady-state performance. The tracking performance of the solar photovoltaic system is analysed and compared for Boost, Cuk, and SEPIC converters using the fuzzy logic-based Incremental Conductance MPPT technique [1][13].

II METHODOLOGY

In isolated photovoltaic (PV) systems, DC-DC converters are crucial for reliable operation and efficient power transfer. Converters such as Boost, Cuk, and SEPIC are essential for regulating voltage and ensuring compatibility between the PV array and the load. This study employs these advanced DC-DC converters alongside a fuzzy-based Incremental Conductance (INC) MPPT algorithm to enhance system performance. This hybrid approach improves voltage regulation, dynamic response, overall efficiency, and system reliability. The methodology evaluates the performance of each converter topology by analysing its ability to optimize power extraction under varying environmental conditions. The selection of the converter is based on specific system requirements, with each topology offering unique benefits. For example, Boost converters are effective for stepping up voltage in high-voltage applications, while Cuk and SEPIC converters provide greater versatility by allowing both step-up and step-down voltage adjustments. This study systematically examines the impact of these converters on tracking efficiency, stability, and energy transfer, offering insights into their suitability for various operational scenarios.

A. INCREMENTAL CONDUCTANCE MPPT METHOD

The Incremental Conductance (INC) method is a widely used Maximum Power Point Tracking (MPPT) technique in photovoltaic (PV) systems. It is based on the fact that the slope of the power-voltage (P-V) curve of a solar PV array is zero at the Maximum Power Point (MPP), positive on the left side of the MPP, and negative on the right side.

The following equations summarize the incremental conductance method

$P = VI$ ………………… (1)

$\frac{dP}{dV} = I + \frac{VdI}{dV}$…………… (2)

$\frac{I}{V} = -\frac{dI}{dV}$………………… (3)

At the MPP, the slope of the P-V curve is zero:

$\frac{dP}{dV} = 0$ ……………….. (4)

Thus,

$\frac{I}{V} = -\frac{dI}{dV}$ ………………. (5)

When dP/dV > 0, i.e., I/V > −dI/dV, the voltage needs to be incremented, and when dP/dV < 0, i.e., I/V < −dI/dV, the voltage needs to be decremented. A flowchart of the incremental conductance method for MPPT is shown in Figure 1. For the conventional INC method, the voltage adjustment involves a fixed, small increment or decrement [6][10][11].

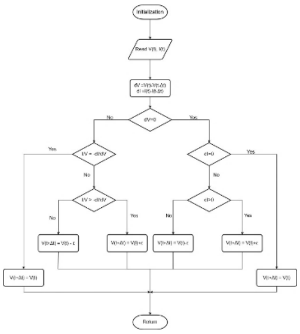

Figure 1: Flowchart of the incremental conductance MPPT method.

B. FUZZY LOGIC ALGORITHM FOR INC MPPT METHOD

The basic operation of a fuzzy controller involves converting precise inputs into fuzzy values through a process called fuzzification, which uses membership functions to determine the degree of membership. Using the rule base and the degrees of membership, the inference engine generates fuzzy outputs through implication and aggregation techniques. These fuzzy outputs are then converted back into crisp outputs using a defuzzification method, such as the centre of area approach [3][5][13].

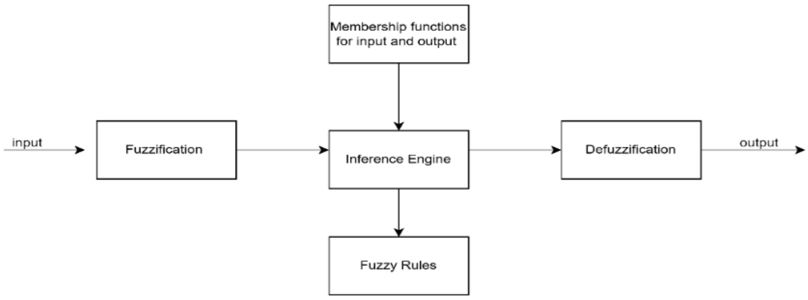

Figure 2: Overview of a Fuzzy logic control system

In this study, a Fuzzy Logic Controller (FLC) is utilized to dynamically adjust the step size for voltage increments or decrements in the Incremental Conductance (INC) Maximum Power Point Tracking (MPPT) method. The algorithm defines five distinct regions based on their proximity to the Maximum Power Point (MPP). These regions, illustrated on power-voltage (P-V) and current-voltage (I-V) curves under standard test conditions, are designated as R1, R2, R3, R4, and R5 [3][5][12].

The voltage ranges for these regions are as follows:

- **R1**: Voltage significantly lower than MPP voltage (Vmpp).
- **R2**: Voltage slightly lower than Vmpp.
- **R3**: Voltage very close to Vmpp.
- **R4**: Voltage slightly higher than Vmpp, mirroring R2 on the other side of Vmpp.
- **R5**: Voltage significantly higher than Vmpp, mirroring R1 on the other side of Vmpp.

The algorithm uses two fuzzy inputs: the ratio of PV current to PV voltage (I/V) and the ratio of their derivatives (dI/dV). The fuzzy output is the variable step size of voltage adjustment, which is implemented through a change in the duty cycle of DC-DC converters such as Boost, Cuk, or Sepic converters. The step size adjustment, denoted as ΔD, is controlled based on the fuzzy inputs and a rule base [3][5][13].

- The intuitive decision rules for selecting an appropriate voltage step size (Vstep) are as follows:
- If dP/dV 0, i.e., I/V $-dI/dV$ (region $R1$), the suitable V_{step} is positive big (PB).

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- If $dP/dV > 0$, i.e., $I/V > -dI/dV$ (region $R2$), the suitable V_{step} is positive small (PS).
- If $dP/dV \approx 0$, i.e., $I/V \approx -dI/dV$ (region $R3$), the suitable V_{step} is very small (VS).
- If $dP/dV < 0$, i.e., $I/V < -dI/dV$ (region $R4$), the suitable V_{step} is negative small (NS).
- If dP/dV 0, i.e., I/V $-dI/dV$ (region $R5$), the suitable V_{step} is negative big (NB).

TABLE 1: Fuzzy rules of generating the variable step duty cycle for INC method with two input I/V and dI/dV.

I/V \ dI/dV	VL	L	VC	H	VH
VL	PB	PS	PS	VS	NS
L	PB	PS	VS	NS	NB
VC	PB	PS	VS	NS	NB
H	PB	PS	VS	NS	NB
VH	PB	PS	PS	NS	NB

The fuzzy rules are designed to determine an appropriate voltage step size (Vstep) based on the fuzzy inputs I/V and dI/dV. To illustrate the reasoning behind these rules, consider the following example: If I/Vand dI/dV are significantly lower (Very Low, VL) compared to their values at the Maximum Power Point (MPP), corresponding to region R5 (as depicted in Figure 8), then the condition I/V<−dI/dV applies. This scenario necessitates a large negative Vstep, which translates into a large positive step (PB) in the duty cycle. Essentially, the step size can be inferred from the sum I/V+dI/dV and its respective region, as represented in Figure 8 [3][5][13].
The fuzzy output is defined as the variable duty cycle step (ΔD), which relates to Vstep through the following equations:

$V = (1 - D) * V_{dc}$ …………………….. (6)

$\Delta V = V_{step} = -\Delta D * V_{dc}$ ………………. (7)

In this context, the DC link voltage (Vdc) is assumed to remain constant throughout the study.
The abbreviations used are defined as follows:

- VL: Very Low
- VH: Very High
- NB: Negative Big
- NS : Negative Small
- VS: Very Small
- VC : Very Close
- PB: Positive Big
- PS : Positive Small
- L : Low
- H: High

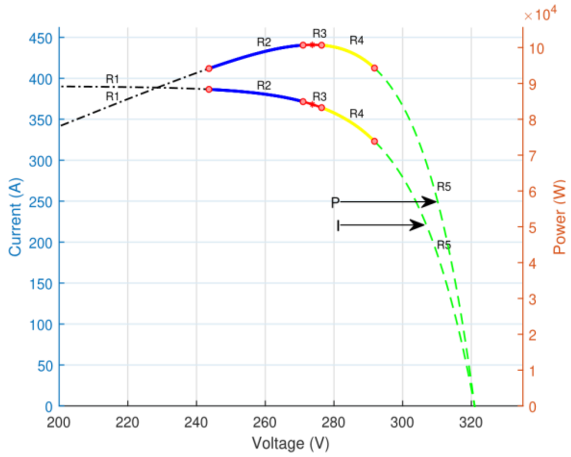

FIGURE 3: Representation of the five proposed regions on the power-voltage and current-voltage relations at the standard test conditions.
The ranges for the fuzzy inputs and output are determined based on their effective values under standard test conditions, as illustrated in Figure 8. However, when factors such as irradiance (G) and cell temperature (Tc) change, the effective values of these fuzzy inputs and outputs also fluctuate. To ensure alignment with the predefined ranges, gain factors are applied to the inputs and output of the fuzzy system. These gains are fine-tuned to optimize their compatibility with the designed fuzzy logic-based variable step INC MPPT method [3][5][12].

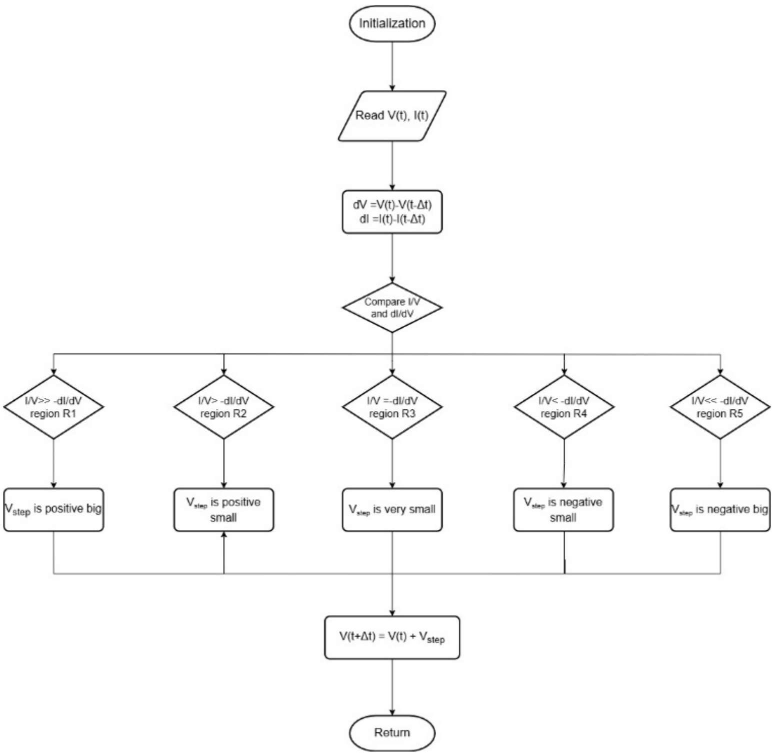

FIGURE 4 : A flowchart of the proposed FLC based variable step size INC MPPT method.

The membership functions for the inputs and outputs are illustrated in Figure 5.

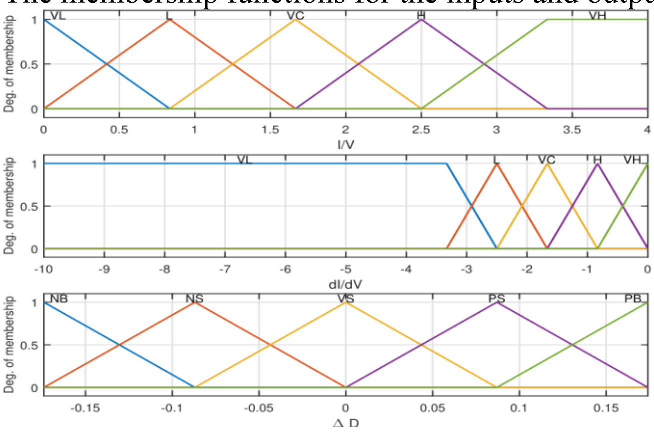

FIGURE 5: The membership functions of inputs and output of FLC based variable step INC method.

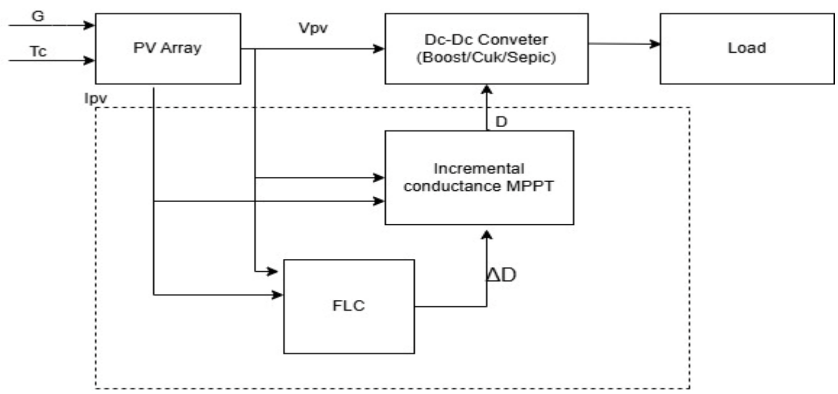

FIGURE 6: An overview of the stand-alone PV array with the proposed FLC based INC MPPT method.

III APPLICATION OF FLC BASED INC MPPT FOR DC-DC CONVERTERS

The fuzzy inputs and output are defined based on their effective values under standard test conditions, as depicted in Figure 8. However, variations in solar irradiance (G) and cell temperature (Tc) cause these effective values to change. To ensure compatibility with the defined ranges, gain factors are applied to the inputs and output of the fuzzy system. These gain factors are adjusted and optimized to enhance their compatibility with the fuzzy logic-based variable step INC MPPT method [1][2][5].
For implementing the proposed FLC-based variable step INC MPPT method, a modified MATLAB model of the Kyocera Solar KC200GT PV array is utilized. This model consists of three parallel strings, each containing 10 modules connected in series. Figure 6 provides an overview of the stand alone PV array model, which incorporates the proposed MPPT algorithm. The system includes a PV array, a DC-DC converter (Boost, Cuk, or Sepic), an INC MPPT controller, and the load. The FLC block supplies the INC MPPT method with a variable adjustment to the duty cycle at each step, based on the fuzzy inputs. The INC MPPT then determines the duty cycle needed to optimize the PV voltage. For simulation purposes, the environmental factors considered are solar irradiance (G) and cell temperature (Tc) [3][12][13].

IV MATHEMATICAL MODELLING

A. BOOST CONVERTER

The operation of a boost converter can be divided into two modes:
1. When the switch is ON: The inductor stores energy from the input supply.
2. When the switch is OFF: The energy stored in the inductor is transferred to the load through the diode [4].

Modelling Equations

$(1-D)=\frac{V_s}{V_a}$ …………….. (8)

where D is the duty cycle (D = Ton / (Ton + Toff)).

$\Delta I=\frac{V_s D}{fL}$ ………………….. (9)

$\Delta V_c=\frac{I_a D}{fC}$ ………………. (10)

B. CUK CONVERTER

The operation of a Cuk converter can be divided into two modes:
1. When the switch is ON: Energy is stored in the input inductor while the capacitor discharges to the load.
2. When the switch is OFF: The input inductor transfers energy to the capacitor, which charges for the next cycle [14].

Modelling Equations

$D=\frac{V_a}{V_a-V_s}$ ………………….. (11)

where D is the duty cycle (D = Ton / (Ton + Toff)).

$\Delta I_1=\frac{V_s D}{fL_1}$ ………………… (12)

$\Delta I_2=\frac{V_s D}{fL_2}$ …………………… (13)

$\Delta V_{c1}=\frac{I_s V_s}{(V_s-V_a)fC_1}$ ………………. (14)

$\Delta V_{c2}=\frac{DV_s}{8C_2L_2f^2}$ …………….. (15)

C. SEPIC CONVERTER

The operation of a SEPIC converter can be divided into two modes:
1. When the switch is ON: The input inductor stores energy, and the coupling capacitor transfers energy to the output inductor.

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2. When the switch is OFF: The stored energy in the inductors is transferred to the load and the coupling capacitor [9].

Modelling Equations

$$V_o = \frac{DV_s}{1-D} \text{ .... (16)}$$

where D is the duty cycle (D = Ton / (Ton + Toff)).

$$L_1 = \frac{V_s DT}{dIL_1} \text{ .... (17)}$$

$$L_2 = \frac{V_s DT}{dIL_2} \text{ .... (18)}$$

$$C_1 = \frac{I_{in(1-D)}}{f dV_{orpl}} \text{ .... (19)}$$

V RESULTS OF SIMULATION

This work analyses the tracking performance of DC-DC Converters (Boost, Cuk and Sepic) in a standalone PV system using Fuzzy Logic based Incremental Conductance MPPT technique.The converters have been simulated individually with the same MPPT technique at 1000w/m^2 irradiance and 25°C temperature at an input voltage of 260V and input current of 23A with a switching frequency of 25kHz. The outputs have been observed using MATLAB.

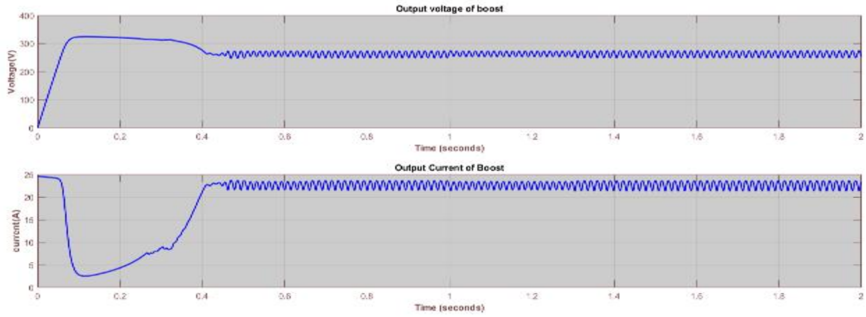

Figure 7 : The output voltage and current of standalone PVsystem using boost converter

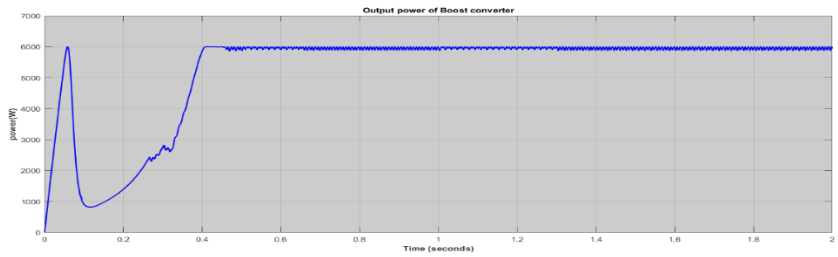

Figure 8 : The power output of stand alone PV system using boost converter

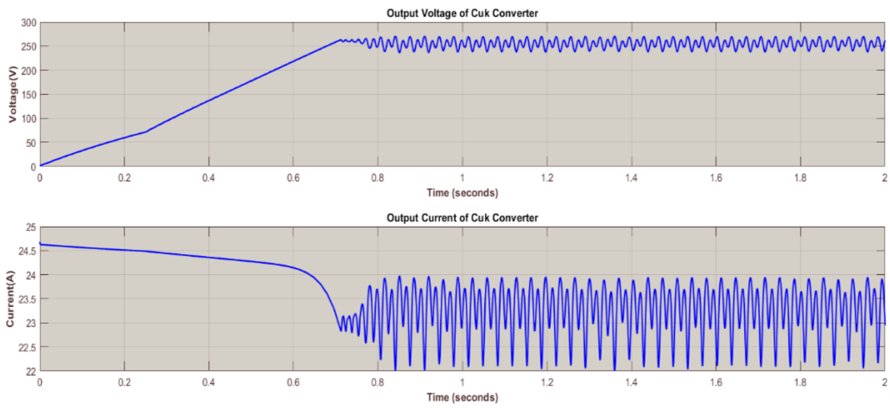

Figure 9: The output voltage and current of standalone PVsystem using cuk converter

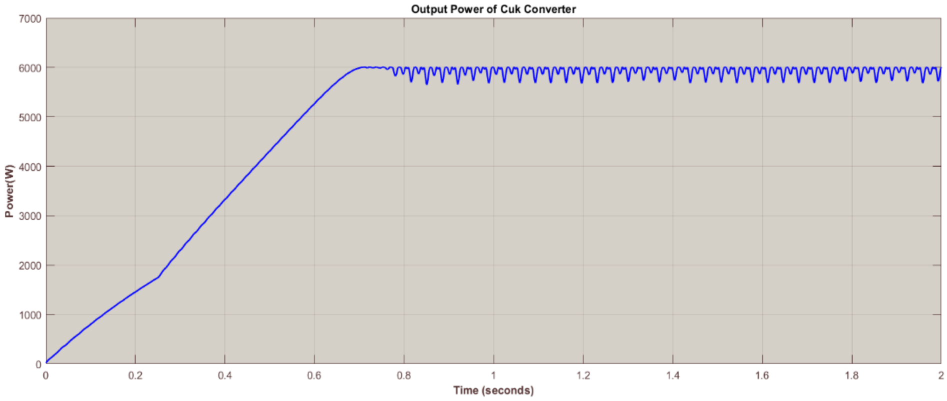

Figure 10 :The power output of stand alone PV system using cuk converter

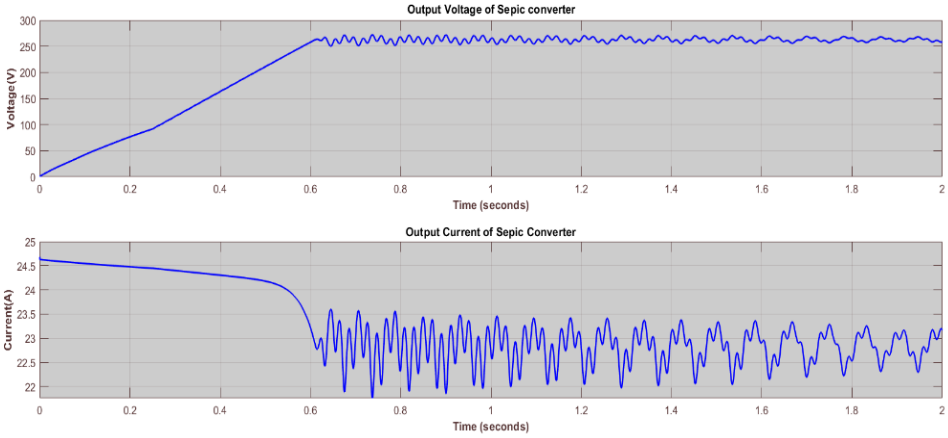

Figure 11: The output voltage and current of standalone PVsystem using sepic converter

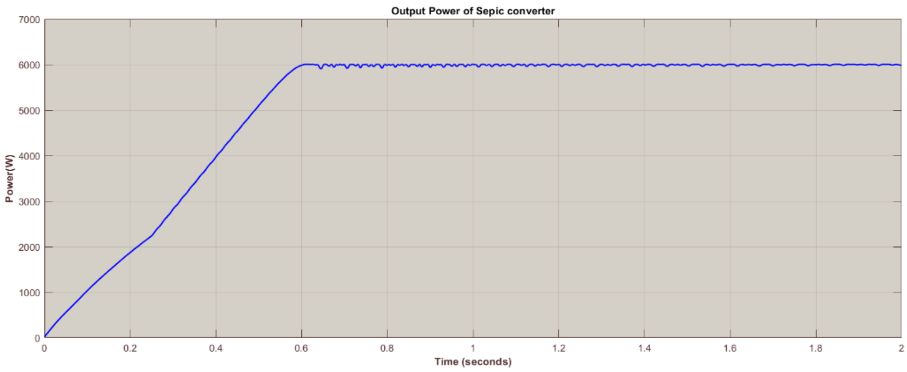

Figure 12: The power output of stand alone PV system using sepic converter

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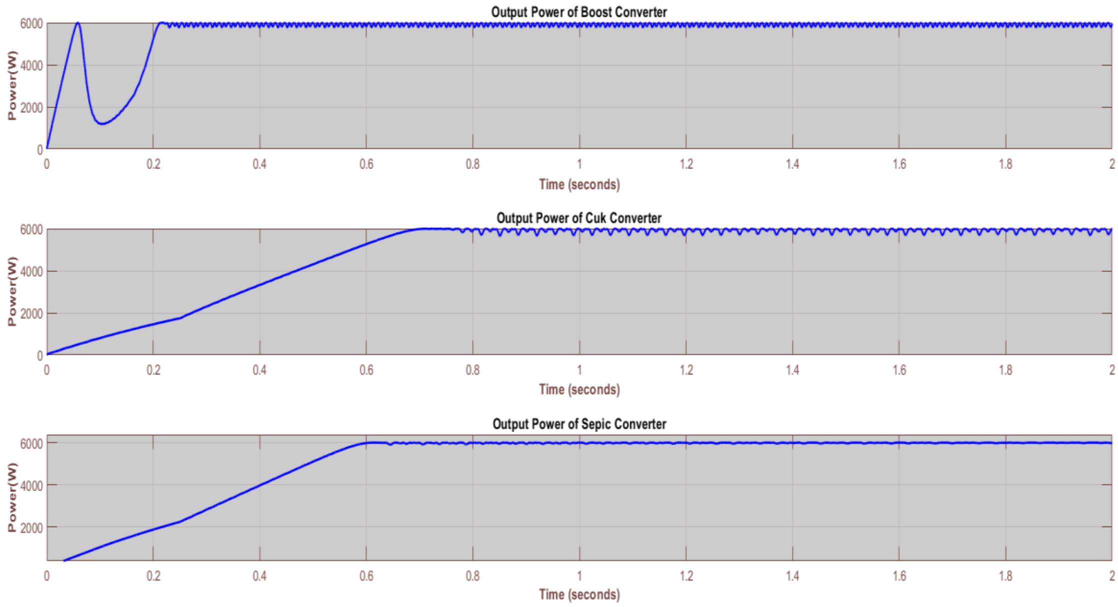

Figure 13: Comparision of output power of converters using FLC based INC MPPT technique

The Figure 13 compares the output power of a PV standalone system using different converters (Boost, Cuk, and Sepic) with a fuzzy logic-based incremental conductance MPPT. The tracking performance of these converters has been analyzed based on this comparison.

Table 2 :Comparision of tracking performance of converters for standalone PV system.

PARAMETER	Boost converter	Cuk converter	Sepic converter
1.Over Shoot	0.057 sec	0.691sec	0.6sec
2. Convergence Speed	Fast(0.227sec)	Slow (0.757sec)	Moderate (0.627sec)
3.Tracking Accuracy	low	moderate	high
4.No Of Oscillations	high	moderate	low
5.Efficiency	99.2%	99.5%	99.8%

From Table 2 The Boost converter offers the fastest response but compromises on tracking accuracy and stability, while the Cuk converter has slower performance with moderate accuracy and oscillations. The Sepic converter excels in tracking accuracy, stability, and efficiency, making it the most balanced and reliable option.

VI CONCLUSION

The tracking performance of boost, Cuk, and SEPIC converters using a fuzzy logic-based INC MPPT method has been analyzed from the simulation results for a PV stand alone system. From the analysis the following conclusions has been drawn

The **Boost converter** demonstrates the fastest convergence speed (0.227 sec) and minimal overshoot (0.057 sec), making it suitable for applications requiring rapid response times. However, it exhibits low tracking accuracy and a high number of oscillations, which may lead to reduced stability in the system.

The **Cuk converter**, while having a moderate tracking accuracy and fewer oscillations compared to the Boost converter, is the slowest in terms of convergence speed (0.757 sec) and has the longest overshoot duration (0.691 sec). These characteristics indicate a slower response, which might not be ideal for dynamic conditions.

The **Sepic converter** achieves the highest tracking accuracy and the lowest number of oscillations, ensuring superior stability and precision in MPPT tracking. It also offers the highest efficiency (99.8%), making it the most energy-efficient option. While its convergence speed (0.627 sec) and

overshoot duration (0.6 sec) are moderate, these values are a trade-off for its high tracking performance and efficiency.
In conclusion, for applications prioritizing **stability, accuracy, and efficiency**, the Sepic converter is the most suitable choice. Conversely, the Boost converter is preferable for applications requiring **rapid response** but can compromise on tracking accuracy and stability. The Cuk converter, with its moderate characteristics, provides a balanced but less optimized solution for the given criteria.

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