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Comparative Analysis of Cuk, SEPIC, and Cuk-Sepic Fused Converters with Fuzzy MPPT Algorithm for Photovoltaic Systems

Shaik Munthaz,Dr. A. Raghuram, Heena Parveen

Electrical and Electronics Engineering , Jawaharlal Nehru Technological University , Hyderabad , Telangana, India

Abstract

To enhance the reliability and performance of photovoltaic (PV) systems, this paper offers an in-depth comparative analysis of Cuk, SEPIC, and a novel Cuk-SEPIC fused converter. This converter is integrated with a Fuzzy Logic Control (FLC)-based Maximum Power Point Tracking (MPPT) method for a solar system designed to support a DC load. Solar energy, a valuable renewable resource, necessitates effective power electronics for DC output adaption. Traditional Cuk and SEPIC converters provide unique voltage outputs: negative for Cuk and positive for SEPIC. The revolutionary Bipolar Cuk-SEPIC converter combines two designs and uses a single switch to create twin outputs with opposing polarities, considerably lowering input current ripple and increasing PV system efficiency. This bipolar DC connection provides reliable performance, making it appropriate for both AC and DC microgrids. Using FLC-based MPPT, the system dynamically changes converter duty cycles to optimum power under changing conditions. The system's performance is evaluated using MATLAB/SIMULINK .

Keywords: Photovoltaic (PV) Systems, Maximum Power Point Tracking (MPPT), Fuzzy Logic Control (FLC) , DC-DC Converters.

1. Introduction

The increasing need for clean and renewable energy has driven the exploration of photovoltaic (PV) systems as a possible alternative to conventional fossil fuels[1]. Despite the inherent variability of solar irradiance and temperature demands the use of advanced power electronics to optimize energy extraction and improve PV system performance[2]. DC-DC converters are important components in this area because they adjust the output voltage to fit the load's requirements, whether it is a DC microgrid, an AC grid link (via an inverter), or direct DC loads.

Traditional DC-DC converters, such as the Cuk and SEPIC topologies, have found widespread use in PV systems due to their unique benefits[3]. The Cuk converter, noted for its capacity to produce a negative output voltage in relation to the input, has intrinsic input current ripple reduction, which is useful for PV arrays. In contrast, the SEPIC converter produces a positive output voltage, which allows for direct integration with positive-ground systems.

To address the limits of single-polarity outputs, a unique hybrid architecture known as the Cuk-SEPIC fused converter has evolved. This novel design cleverly merges the Cuk and SEPIC structures into a single entity, with a single switch producing both positive and negative output voltages[4]. This bipolar output capability, along with decreased input current ripple, allows the Cuk-SEPIC fused converter suitable for the applications that may include both AC and DC loads.Implementing a Maximum Power Point Tracking (MPPT) algorithm is essential for the optimal performance of any photovoltaic system[5]. This algorithm constantly tracks the operating condition of the PV array and adjusts the duty cycle of the DC-DC converter to ensure the system operates at maximum power transfer, thereby enhancing energy collection.Fuzzy Logic Control (FLC)-based MPPT algorithms have gained favor in this area because of their ability to handle the nonlinearities and uncertainties inherent in photovoltaic systems[6]. This study offers a comparative evaluation of the Ćuk, SEPIC, and fused Ćuk-SEPIC converters, all of which are integrated with an MPPT algorithm based on fuzzy logic control (FLC). The simulation was performed using MATLAB/Simulink system simulation software.

The organization of the paper is outlined as follows: Section II presents the main block diagram of the proposed model.Section III describes the control techniques used. Section IV contains the discussion, whereas section V has the simulation results. Section VI describes the proposed system's conclusion.

2. Designed Circuit

Figure 1 illustrates a basic block diagram of a PV system, incorporating a DC-DC converter along with an MPPT control mechanism.The photovoltaic array provides DC power in response to temperature and irradiance.The function of the DC-DC converter is to adjust the output voltage of the photovoltaic array to match the requirements of the DC load.An MPPT fuzzy control block, coupled with a PWM generator, dynamically adjusts the converter's duty cycle to maximize power extraction from the PV array under varying environmental conditions.

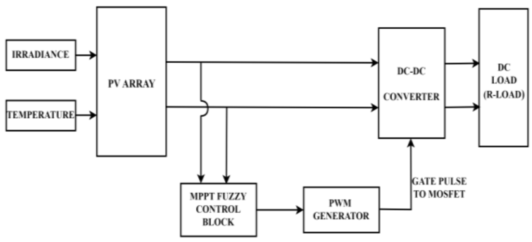

Figure 1. Block diagram of the photo voltaic (PV) system with DC-DC converter and MPPT control.

A. Photo Voltaic System

Solar panels are arranged in arrays to harness sunlight and convert it into electricity. PV array consists of many solar panels connected in a grid-like way[7].These panels are linked in series to create strings, which are subsequently connected in parallel. A solar PV array of 5.3kW peak power is considered[8]. Table II specifies the parameters of the PV array. Figure 2 shows the equivalent circuit of a solar cell.

The characteristic equation for output current is:

$$I = I_{PV} - I_O \left[exp\left(\frac{q(V+IR_S)}{\propto KT}\right) - 1 \right] - \frac{V+IR_S}{R_{sh}} \quad (1)$$

Where:

I_{PV}: Photo-induced current;

I_{sh}:Shunt current;

q : Electron charge equals1.6*10^{-19};

K : Boltzmann constant equals 1.38*10^{-23}J/K;

I_O: Reverse saturation current;

R_s: Series resistance;

R_{sh}: Shunt resistance;

T: ambient temperature(℃)

∝ : ideal factor of a diode ranges from 1 to 2, with a typical value of 1.3.

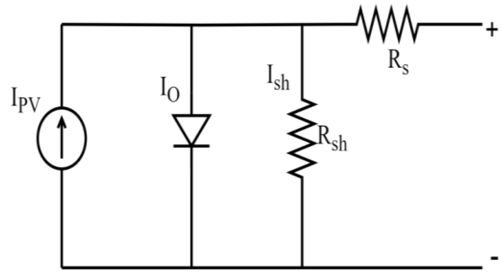

Figure 2. Single-diode solar photovoltaic cell model

B. Design of Converter

B.1. Cuk converter : The Ćuk converter is a type of DC-DC converter that is recognized for its ability to produce a negative output voltage relative to its input.The Cuk converter can perform both buck(step-down) and boost (step-up) voltage transformations,guaranteeing [9] that the output voltage stays steady despite variations in the input voltage. The Cuk converter's functioning is based on the transfer of energy between two inductors and one capacitor[10]. A switch, most frequently a MOSFET transistor (S1), controls the flow of current through inductors, resulting in energy transfer.

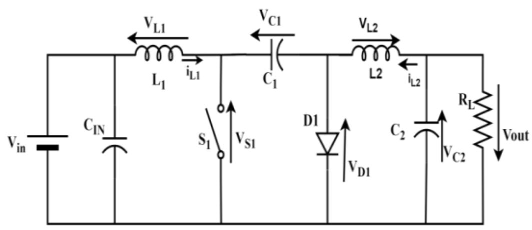

Figure 3. Circuit diagram of Cuk converter

The cuk converter's circuit is shown in Figure 3. For designing the circuit, (2), (3) and (4) are used which are derived from the circuit diagram to determine the appropriate component values.

$$V_{out} = \left(\frac{-D}{1-D}\right) \times V_{in}$$

(2)

$$L_1 = \frac{V_{in}\times D}{\Delta I_{L1}\times f_s} \qquad L_2 = \frac{V_{out}}{\Delta I_{L2}\times f_s}\times(1-D) \quad (3)$$

$$C_1 = \frac{I_{in}\times(1-D)}{\Delta V_{C1}} \qquad C_2 > \frac{1-D}{8\times(0.01)}\times T_s$$

(4)

B.2. SEPIC converter : The Single-Ended Primary-Inductance Converter (SEPIC) can adjust the output voltage to be higher, lower, or the same as the input voltage[11]. This SEPIC converter integrates buck and boost converters, enabling it to handle different input voltages while maintaining a stable output voltage[12]. The control switch (S1)'s duty ratio regulates the SEPIC output.The SEPIC design allows energy transmission between capacitive and inductive components, making voltage levels easier to change. Switch S1, a MOSFET transistor, controls the amount of energy delivered.

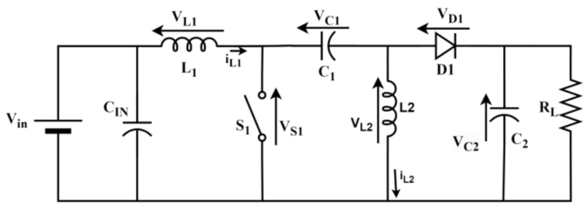

Figure 4. Diagram of the SEPIC converter circuit

Figure 4 displays the circuit diagram of the SEPIC converter. For designing circuit, (5), (6) and (7) are used.

$$V_{out} = \left(\frac{D}{1-D}\right) \times V_{in}$$

(5)

$$L_1 = \frac{V_{in}\times D}{\Delta I_{L1}\times f_s} \qquad L_2 = \frac{V_{in}\times D}{\Delta I_{L2}\times f_s}\times(1-D)$$

(6)

$$C_1 > \frac{D\times I_{out}}{\Delta V_{C1}\times f_s} \qquad C_2 > \frac{D\times I_{out}}{\Delta V_{C2}\times f_s} \quad (7)$$

B.3.Cuk-SEPIC fused converter: The Cuk-SEPIC fused converter is a combined DC-DC converter that integrates the structures of both the Cuk and SEPIC converters into a unified system.This one-of-a-kind design can generate output voltages of both polarities (Positive output from the SEPIC portion and negative output from the Cuk portion of the converter), making it ideal for applications that require various voltage levels, such as microgrids[13]. The converter uses a single switch to regulate the power transfer between its inductive and capacitive elements. One of the primary benefits of the Cuk-SEPIC fused converter is it's versatility in voltage conversion, i.e., Vo/Vin=2D/D-1[10]. The Cuk-SEPIC fused converter provides numerous advantages, including bipolar output, high voltage gain, low input and output current ripple, and single-switch operation[14].

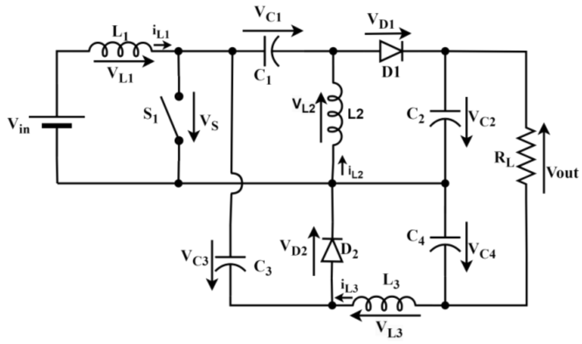

Figure 5. Schematic diagram of the Cuk-SEPIC converter

Figure 5 demonstrates the circuitry for the Cuk-SEPIC converter.To design circuit,(8), (9) and (10) are used.

$$V_{out} = \frac{2D}{(1-D)} \times V_{in}$$

(8)

$$L_1 = \frac{V_{in}\times D}{\Delta I_{L1}\times f_s} \qquad L_2 = \frac{V_{in}\times D}{\Delta I_{L2}\times f_s}$$

(9)

$$C_1, C_3 = \frac{D\times I_{out}}{\Delta V_{C1}\times f_s} \qquad C_2, C_4 = \frac{D}{\left(R\times f_s\times\left(\frac{\Delta V_{C2}}{V_{out}}\right)\right)}$$

(10)

3. The Control System

A. Mppt Control Algorithm

MPPT is a vital technology that dynamically adjusts the operating point of a photovoltaic system to maximize power output under changing conditions[15]. MPPT algorithms effectively optimize energy harvesting, increasing the total effectiveness and affordability of a PV system. Without MPPT, a large portion of accessible solar energy is squandered, resulting in inferior performance and a worse return on investment.

B. FLC - BASED MPPT IMPLEMENTATION

Fuzzy Logic Control (FLC) is a practical approach for system governance that uses human-like reasoning. Unlike traditional control approaches that depend on precise mathematical representations, FLC works with language variables and fuzzy sets, which reflect the natural imprecision and uncertainties of real-world situations[16]. This makes FLC ideal for MPPT in solar PV systems, where sun irradiance and temperature vary unpredictably.

The Fuzzy Logic Controller (FLC) uses two inputs: error (E(k)) and the change in error (ΔE(k)), which are determined as follows.

$$E(k) = \frac{P(k)-P(k-1)}{V(k)-V(k-1)} \quad (11)$$

$$\Delta E(k) = E(k) - E(k-1) \quad (12)$$

P(k) and V(k) denote instantaneous power and voltage of the panel, respectively.

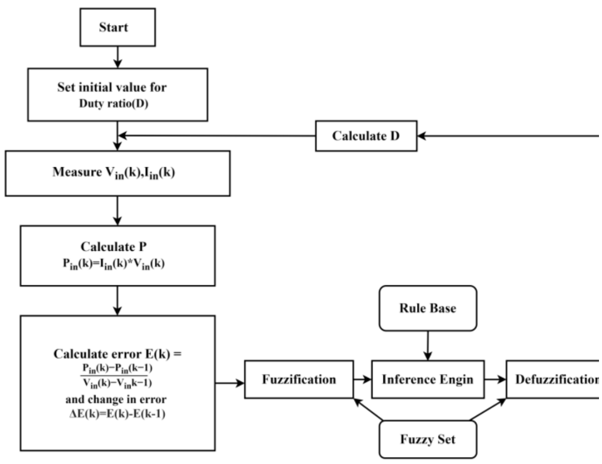

Figure 6. Flowchart for the Fuzzy Logic Controller system

The FLC-based MPPT algorithm follows three distinct stages:

1) Fuzzification
2) Rule Evaluation (Inference Engine)
3) Defuzzification

Fuzzification converts crisp input variables, like error (E(k)) between current and prior power and error change (ΔE(k)), into fuzzy sets utilizing membership functions that assign degrees of membership to linguistic concepts. During the rule evaluation stage, a set of predefined fuzzy rules based on the PV system's P-V characteristics are utilized to determine the appropriate action in the form of a fuzzy output. The defuzzification stage converts fuzzy output to a crisp value, commonly representing the duty cycle (D) for the DC-DC converter.This value then utilized for optimizing the extraction of power from the photovoltaic array[17], [18].

The fuzzy logic controller (FLC) employs 49 rules, utilizing triangular membership functions for two inputs (error and change in error) and one output (change in duty cycle), to precisely track the maximum power point (MPP).The membership functions are classified into categories such as NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big).Table I provides a detailed list of the fuzzy rules.Rules are evaluated using the Mamdani

TABLE I . FUZZY RULE TABLE

		ΔE(k)						
		PB	PM	PS	ZE	NS	NM	NB
E(k)	PB	PB	PB	PB	PB	PM	PS	ZE
	PM	PB	PB	PB	PM	PS	ZE	NS
	PS	PB	PB	PM	PS	ZE	NS	NM
	ZE	PB	PM	PS	ZE	NS	NM	NB
	NS	PM	PS	ZE	NS	NM	NB	NB
	NM	PS	ZE	NS	NM	NB	NB	NB
	NB	ZE	NS	NM	NB	NB	NB	NB

inference approach, and defuzzification is carried out with the gravity method.Figure 3 depicts the overall fuzzy control mechanism, which includes a flowchart and Simulink model.

4. Simulation of the Proposed System

The Simulink models shown in Fig 7, 8, and 9 were created and run using the MATLAB/Simulink environment.Three distinct DC-DC converters have been implemented: the CUK converter (Fig 7), the SEPIC converter (Fig 8), and the Cuk-SEPIC converter (Fig 9). The suggested framework analyzes the Ćuk, SEPIC, and Ćuk-SEPIC converters, incorporating a Maximum Power Point Tracking (MPPT) algorithm based on Fuzzy Logic Control (FLC) for a solar photovoltaic system[8], [9].A photovoltaic (PV) panel with a power rating of 5.3 kw is the primary energy source. The solar panel is exposed to 1000 W/m² of irradiation at a temperature of 25°C.

The converter is powered by the output of the PV panel and receives a gating pulse from the system's PWM converter. Table II shows the circuit parameters designed using the equations presented for each converter.To minimize ripple in the output voltage, each model includes a capacitor connected across the photovoltaic array. This capacitor has a constant value of 0.1mF.Figures 11 through 15 present the output graphs for each of the converters.The graphs illustrate the voltage and current outputs for the photovoltaic array as well as for the DC-DC converter

Figure 7. Simulink model of DC-DC Ćuk converter

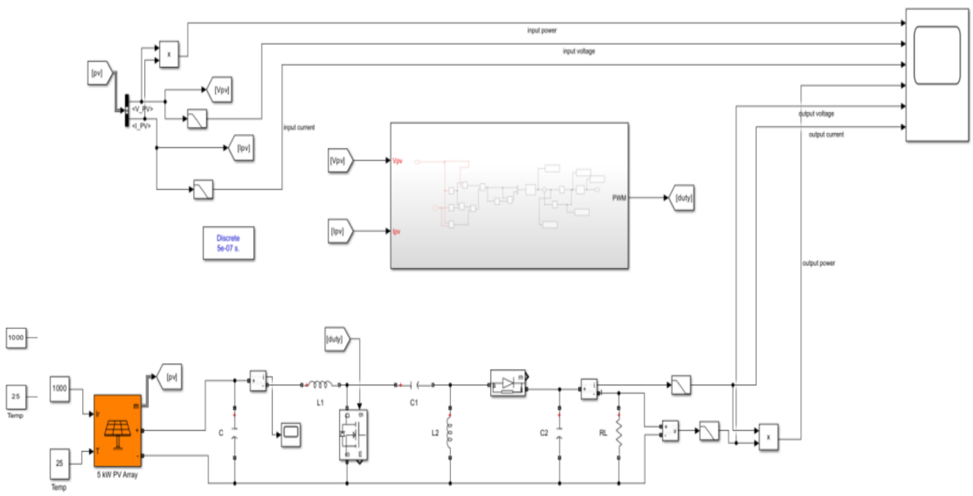

Figure 8. Simulink model of DC-DC SEPIC converter

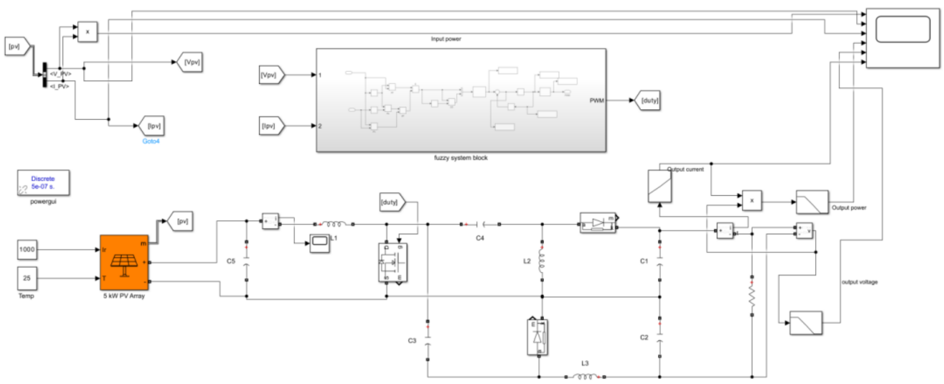

Figure 9. Simulink model of Cuk-SEPIC converter

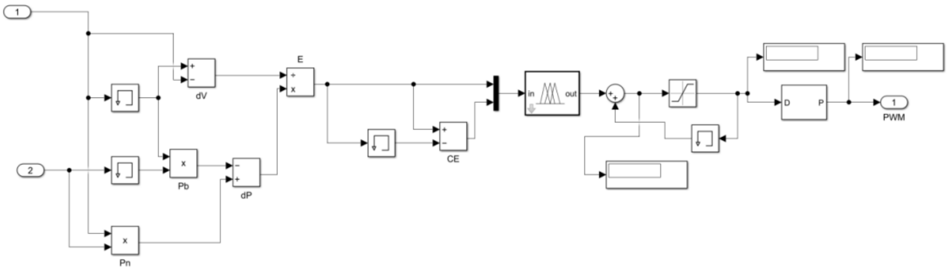

Figure 10. Simulink model of Fuzzy Logic MPPT Controller

TABLE II. SPECIFICATIONS OF THE MODE

Type of Converter	Parameters		Value
Solar PV Array	Open circuit voltage, (V_{OC})		21V
	Short circuit current, (I_{SC})		7.1A
	Voltage at MPP, (V_{mpp})		17V
	Current at MPP, (I_{mpp})		6A
	Power a MPP, (P_{mpp})		5.3kW
	Parallel Strings, (N_P)		2
	Series Strings, (N_S)		26
CUK converter	Input Voltage (V_{in})		420V
	Output Voltage (V_{out})		544V
	Inductors	L_1	0.905 mH
		L_2	1.63 mH
	Capacitors	C_1	0.883 µF
		C_2	0.0307 µF
	Switching Frequency (Fs)		100 kHz
	Load Resistor (R_L)		67.93 Ω
	Input Voltage (V_{in})		420V
	Output Voltage (V_{out})		565V
	Inductors	L_1	0.905 mH

SEPIC converter		L_2	1.63 mH
	Capacitors	C_1	0.883 µF
		C_2	0.883 µF
	Switching Frequency (F_s)		100 kHz
	Load Resistor (R_L)		67.93 Ω
CUK-SEPIC converter	Input Voltage (V_{in})		420V
	Output Voltage (V_{out})		980 Ω
	Inductors	L_1	5.9mH
		$L_2 = L_3$	0.1179
	Capacitors	$C_1 = C_3$	0.265µF
		$C_2 = C_4$	0.133µF
	Switching Frequency (F_s)		100 kHz
	Load Resistor (R_L)		188.68Ω

5. Simulation Results

This section presents the outcomes of simulating the proposed system using Cuk, SEPIC, and Cuk-SEPIC converters . Figures 11, 12, and 13 show the input voltage, input current, and input power, as well as the output voltage, output current, and output power with the CUK, SEPIC, and Ćuk-SEPIC converters connected.

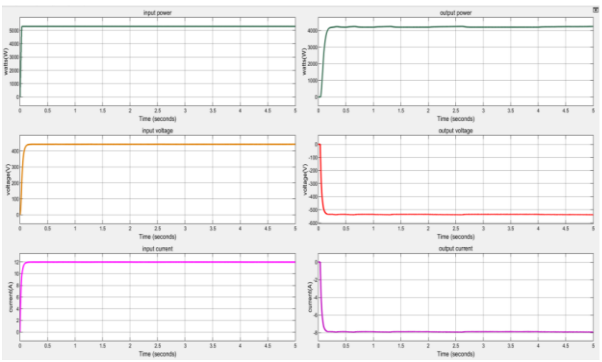

Figure 11. Waveforms of the Cuk Converter with PV array

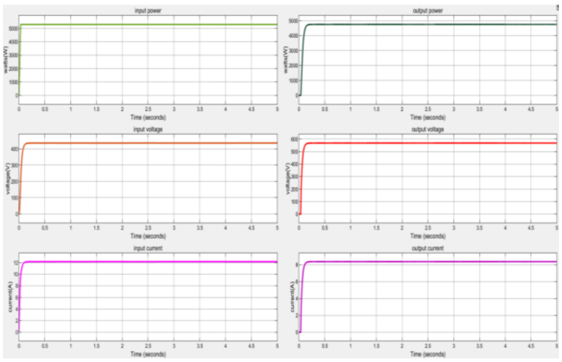

Figure 12. Waveforms of the SEPIC Converter with PV array

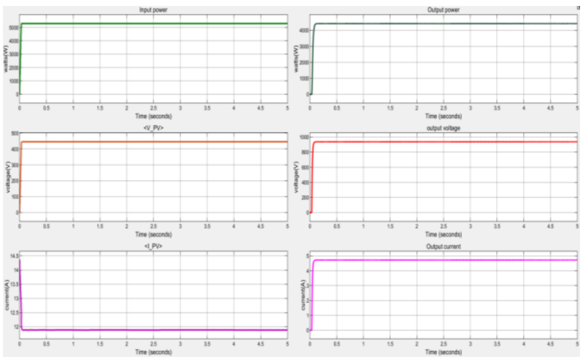

Figure 13. Waveforms of the Cuk-SEPIC Converter with PV array

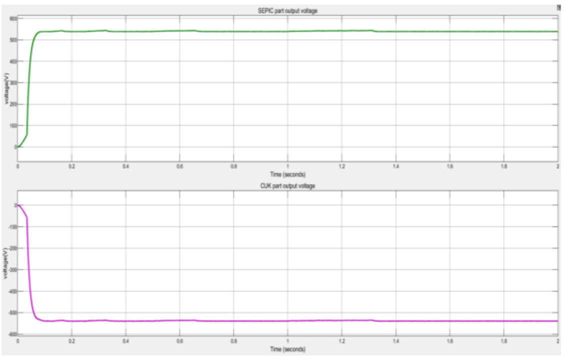

Figure 14. Cuk-SEPIC converter, producing both positive and negative voltage outputs.

The Cuk-SEPIC fused converter demonstrates superior response dynamics in comparison to conventional Cuk and SEPIC converters, as depicted in Figure 15.

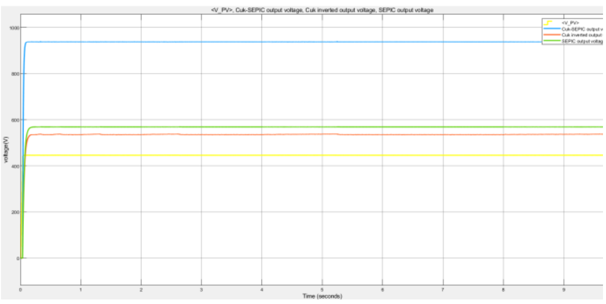

Figure 15. Waveforms of Solar PV , Cuk-SEPIC ,Sepic and Cuk output voltages.

TABLE III. Comparative analysis of DC-DC converters

S.No	Parameters	Cuk converter	SEPIC converter	Cuk-SEPIC Fused converter
1	Outputvoltage (v)	544	565	976
2	Rise time(ms)	43.3	36.5	6.1
3	Peak time(ms)	655.6	2626.5	329.5
4	Settle time(sec)	0.3	0.4	0.2

6. Conclusion

Cuk, SEPIC, and Cuk-SEPIC fused converters with FLC-MPPT were compared using extensive simulations, yielding substantial insights into their performance characteristics. The Cuk-SEPIC fused converter identified as the most promising architecture, with higher power output, efficiency, and MPP tracking capabilities than its individual competitors. Its unique ability to deliver both positive and negative output voltages, combined with low input current ripple, makes it an appealing option for a variety of applications, specially microgrid systems where flexibility and efficiency are critical. The FMPPT algorithm's ability to maximize power extraction from the PV array, particularly under unpredictable conditions, highlights its applicability to real-world PV system.

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