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DOI: https://doi.org/10.64388/IREV9I10-1716322

Closed-Loop Performance Evaluation of Boost, Cuk and Sepic Dc–Dc Converters Using Simulation-Based Analysis

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Abstract- In this paper, three popular non-isolated DC-DC converter topologies—Boost, Cuk and SEPIC, converters are thoroughly modelled, mathematically derived, and their closed-loop performance compared. In contrast to traditional simulation-only studies, this work uses the principles of capacitor charge balance and inductor volt-second balance to derive the steady-state voltage conversion ratios. State space averaging and small-signal modelling are then used for control design. LTspice is used and assessed in the presence of load and input disruptions. To ensure a fair comparison, the converters are designed under identical operating conditions. Transient response, stability, ripple behaviour, efficiency trends, and robustness are used to evaluate performance. The findings show that regulation performance is greatly improved by closed-loop control, with simulation showing better disturbance rejection and less overshoot. The article offers design-focused recommendations for controller selection and topology in contemporary power electronic applications.

Index Terms- DC–DC converters, boost converters, Cuk converters, SEPIC converters, state-space modelling, small signal analysis and LTspice are examples of index terms.

I. INTRODUCTION

DC-DC converters are really important for systems that use current, like electric cars and renewable energy systems. They help change the voltage when the system is running and make sure the output stays the same.

DC-DC converters are used in aerospace power modules too.

There are kinds of converters like Boost, Cuk and SEPIC converters. These converters can. Increase and then decrease the voltage and they have different effects on the current.

Most studies only look at how these converters work when they're steady and not controlled.

For real world systems we need to understand how they work when they are being controlled and how stable they are. This means we need to use math to understand how they work.

This work looks at how DC-DC converters work when they are being controlled. It uses complete math to compare them which is different, from how it is usually done.

II. LITERATURE REVIEW

Several studies have investigated the performance of non-isolated DC–DC converter topologies for renewable and photovoltaic applications.

In [1], the authors performed a comparative evaluation of Cuk, SEPIC, and Zeta converters for an 80-W mono-crystalline photovoltaic module. Their study included both simulation and experimental validation. While the simulation results indicated Closed-Loop Modeling, Mathematical Derivation, and Comparative Performance Analysis of Boost, Cuk, SEPIC, and Zeta DC–DC Converters extremely high efficiencies exceeding 99% for all three converters, the experimental results revealed significantly lower efficiencies of 80.6%, 83.6%, and 90.7% for Cuk, SEPIC, and Zeta converters, respectively. The discrepancy between simulated and experimental performance highlighted practical loss mechanisms. Among the tested converters, the Zeta topology demonstrated superior real-world efficiency.

In [2], the performance of SEPIC, Luo, and Zeta converters was analyzed by focusing on ripple voltage, switching losses, and efficiency characteristics. The comparative analysis showed that the Zeta converter achieved improved ripple performance and lower switching stress, making it favourable for voltage boosting applications. However, the study did not include closed-loop regulation or disturbance testing.

The work presented in [3] provided a general overview of multiple DC–DC converter topologies, including Buck, Boost, Cuk, and Zeta converters. The author emphasized the inherent advantages and limitations of each topology, concluding that Buck and Boost converters offer costeffective and efficient operation, while Cuk and Zeta converters exhibit reduced ripple characteristics due to continuous current behavior. Nevertheless, the study remained largely descriptive and lacked quantitative dynamic comparison.

In [4], a comparative investigation of Buck-Boost, SEPIC, Cuk, and Zeta converters was conducted in combination with three Maximum Power Point Tracking (MPPT) techniques: perturb and observe, incremental conductance, and fuzzy logic control. The evaluation considered efficiency and settling time under photovoltaic operating conditions. The results indicated that the FLC-based Cuk converter achieved the highest efficiency, while the FLC-Zeta combination provided improved transient response. Although this work incorporated intelligent control, it primarily focused on MPPT performance rather than detailed converter dynamic modeling and stability analysis.

In [5], the authors examined Boost, Buck, Buck-Boost, Cuk, SEPIC, and Zeta converters for photovoltaic systems requiring voltage boosting for medium and high-power applications. The converters were tested across different duty cycle conditions, and output voltages were compared. The study emphasized voltage gain capability and duty-ratio dependency; however, it did not address small-signal modeling or closed-loop controller benchmarking.

In [6], Siddharthan and Balasubramanian conducted a performance evaluation of SEPIC, Luo, and Zeta converters. The study focused on parameters such as ripple voltage, switching losses, and efficiency. The results indicated that the Zeta converter achieved improved ripple characteristics and better overall efficiency compared with the other converters considered. However, the analysis primarily emphasized steady-state behavior and did not include closed-loop control or dynamic performance assessment.

In [7], Besekar presented an overview of different DC–DC converter topologies, including Buck, Boost, Cuk, and Zeta converters. The study highlighted the advantages and limitations of each topology in terms of voltage conversion capability, ripple characteristics, and implementation cost. The author concluded that Buck and Boost converters offer higher efficiency and lower cost, whereas Cuk and Zeta converters provide improved current continuity and reduced ripple. Nevertheless, the work mainly provided a qualitative discussion rather than a detailed analytical comparison.

In [8], Seguel et al. investigated the performance of Buck-Boost, SEPIC, Cuk, and Zeta converters integrated with various Maximum Power Point Tracking (MPPT) algorithms, including perturb-and-observe, incremental conductance, and fuzzy logic control. The study evaluated the converters in terms of efficiency and transient response under photovoltaic operating conditions. The findings showed that the fuzzy logic controlled Cuk converter achieved the highest efficiency, while the Zeta converter exhibited better transient performance when combined with fuzzy control.

In [9], Palanisamy et al. compared the performance of several DC–DC converters, including Boost, Buck, Buck-Boost, Cuk, SEPIC, and Zeta converters, for photovoltaic applications. The converters were tested under different duty-cycle conditions to analyze their voltage boosting capability. The results demonstrated that converter selection depends strongly on the required voltage gain and operating duty ratio. However, the study mainly focused on voltage gain

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DOI: https://doi.org/10.64388/IREV9I10-1716322

characteristics and did not include controller design or stability analysis.

In [10], Erickson and Maksimovic provided fundamental theoretical frameworks for DC–DC converter modeling and analysis. Their work introduced concepts such as state-space averaging, small-signal modeling, and frequency-domain stability analysis, which have become standard tools for designing and controlling switching power converters.

Similarly, Mohan, Undeland, and Robbins in [11] presented comprehensive design methodologies for power electronic converters. Their work explains converter operating principles, switching behavior, and control techniques, providing essential theoretical foundations for the analysis and design of modern DC–DC converter systems.

In [12], Luo and Ye introduced advanced DC–DC converter structures and voltage lift techniques aimed at achieving higher voltage gain and improved efficiency. Their work expanded the conventional converter family by proposing enhanced topologies capable of supporting high-performance energy conversion systems.

In [13], Yi and Wang reviewed various voltage bucking and boosting converter techniques used in modern power electronics applications. The study analyzed multiple converter structures and highlighted their suitability for different power conversion scenarios, emphasizing the importance of topology selection in achieving efficient energy conversion.

In [14], Boonraksa et al. performed a comparative analysis of Cuk, SEPIC, and Zeta converters for photovoltaic systems operating with Maximum Power Point Tracking. Both simulation and experimental investigations were conducted. Although the simulation results suggested efficiencies close to 100%, the experimental results showed practical efficiencies of approximately 80–90%. Among the three converters, the Zeta converter demonstrated the highest experimental efficiency.

III. METHODOLOGY

This section presents the complete methodology adopted for the analysis, modeling, design, closed-loop control, and comparative evaluation of Boost, Cuk and SEPIC DC–DC converters. The approach integrates analytical derivations, circuit-level simulation, control implementation, and quantitative performance assessment using standardized metrics.

A. Selected Converter Topologies

Three non-isolated DC–DC converter topologies are selected due to their relevance in renewable energy and battery-powered systems:

- Boost converter
- Cuk converter
- SEPIC converter

1) Circuit Topologies

All converters employ PWM-controlled MOSFET switching and operate in Continuous Conduction Mode (CCM) to ensure reduced ripple and stable operation.

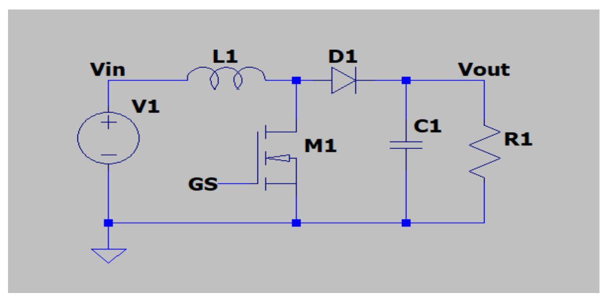

Fig. 1. BOOST CONVERTER

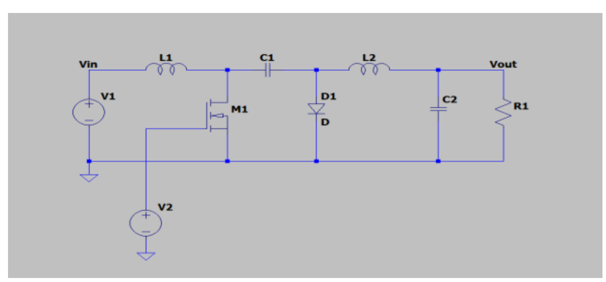

Fig. 2. CUK CONVERTER

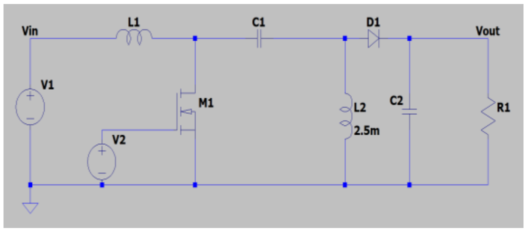

Fig. 3. SINGLE-ENDED PRIMARY- INDUCTOR CONVERTER (SEPIC)

All converters employ PWM-controlled MOSFET switching and operate in Continuous Conduction Mode (CCM) to ensure reduced ripple and stable operation.

B. Operating Specifications

To ensure a fair and meaningful comparison, identical operating conditions are applied to all converter topologies.

Table I – Common Design Specifications

Parameter	Symbol	Value
Input Voltage	V_{in}	24 V
Output Voltage	V_o	48 V
Switching Frequency	f_s	100 kHz
Load Resistance	R	50 Ω
Conduction Mode	–	CCM
Inductor Ripple	ΔI_L	≤ 20%
Voltage Ripple	ΔV_o	≤ 1%

C. Steady-State Mathematical Analysis

Each converter is analyzed using volt–second balance for inductors and charge balance for capacitors under steady-state periodic conditions.

The derived voltage conversion ratios are summarized below.

Table II – Voltage Conversion Ratios

Converter	Conversion Ratio
Boost	$\frac{V_o}{V_{in}} = \frac{1}{1-D}$
Cuk	$\frac{V_o}{V_{in}} = -\frac{D}{1-D}$
SEPIC	$\frac{V_o}{V_{in}} = \frac{D}{1-D}$

These expressions define the operating limits and duty-cycle dependency of each topology.

D. State-Space Averaging and Small-Signal Modeling

To design closed-loop controllers, state-space averaging is applied. Each converter is modeled in two switching states (ON and OFF). The averaged dynamic model is expressed as:

$$\dot{x} = D(A_1 x + B_1 u) + (1-D)(A_2 x + B_2 u)$$

Linearization around the steady-state operating point yields the small-signal model used for control design.

Example: Boost Converter Control-to-Output Transfer Function

$$G(s) = \frac{V_{in}}{(1-D)^2} \cdot \frac{1}{LCs^2 + \frac{L}{R}s + 1}$$

E. Component Design Methodology

Passive components are selected based on ripple and stability constraints.

1) Inductor Design

$$L \geq \frac{V_{in} D}{\Delta I_L f_s}$$

2) Output Capacitor Design

$$C \geq \frac{I_o D}{\Delta V_o f_s}$$

Table III – Designed Component Values

Converter	Inductors	Capacitors
Boost	L = 150uH	C = 220 µF
SEPIC	L1 = L2 = 2.5 mH	C1 = 16.3µF, C2 = 14 µF
Cuk	L1 = 150 uH, L2 = 270uH	C1 = 47uF, C2 = 22uF

F. Simulation Model and Graphical Analysis

All converters are simulated using MATLAB/Simulink with PWM-based switching and feedback control.

ii) Boost Converter Design Calculations

1. Duty Cycle Calculation

$$\boldsymbol{V_o = \frac{V_{in}}{1-D}}$$
$$\boldsymbol{\frac{V_o}{V_{in}} = \frac{1}{1-D}}$$
$$\boldsymbol{\frac{15}{5} = \frac{1}{1-D}}$$
$$\boldsymbol{3 = \frac{1}{1-D}}$$
$$\boldsymbol{1-D = \frac{1}{3}}$$
$$\boldsymbol{D = 1-\frac{1}{3} = \frac{2}{3}}$$
$$\boldsymbol{D = 0.67\ (67\%)}$$

2. Output Current (Assumption)

Assume output power level:

Let,

$$\boldsymbol{I_{out} = 1\,A}$$

3. Input Current Calculation

$$\boldsymbol{P_{in} = P_{out}}$$
$$\boldsymbol{V_{in} \cdot I_{in} = V_{out} \cdot I_{out}}$$
$$\boldsymbol{5 \cdot I_{in} = 15 \cdot 1}$$
$$\boldsymbol{I_{in} = 3\,A}$$

4. Inductor Current Ripple

Assume ripple = 30% of input current

$$\boldsymbol{\Delta I_L = 0.3 \times I_{in}}$$
$$\boldsymbol{\Delta I_L = 0.3 \times 3 = 0.9\,A}$$

5. Inductor Value Verification

$$\boldsymbol{L = \frac{V_{in} \cdot D}{f_s \cdot \Delta I_L}}$$
$$\boldsymbol{L = \frac{5 \times 0.67}{25000 \times 0.9}}$$
$$\boldsymbol{L = \frac{3.35}{22500}}$$
$$\boldsymbol{L \approx 148.8\,\mu H}$$

Given value = 150 µH (Correct & suitable)

6. Output Capacitor Calculation

Assume voltage ripple:

$$\boldsymbol{\Delta V_o = 1\%\ \text{of}\ V_o = 0.15V}$$
$$\boldsymbol{C = \frac{I_{out} \cdot D}{f_s \cdot \Delta V_o}}$$
$$\boldsymbol{C = \frac{1 \times 0.67}{25000 \times 0.15}}$$
$$\boldsymbol{C = \frac{0.67}{3750}}$$
$$\boldsymbol{C \approx 178.6\,\mu F}$$

take value = 220 µF (Safe & better)

7. Load Resistance

$$\boldsymbol{R = \frac{V_o}{I_{out}} = \frac{15}{1} = 15\,\Omega}$$

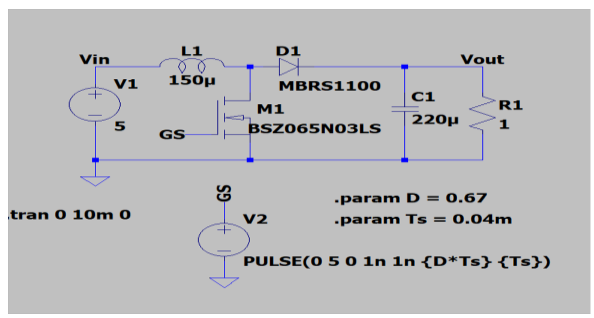

Fig. 4. Simulink diagram of BOOST converter

ii) Cuk Converter Design Calculations

Vin = 12 V

Vout = 24 V

Iout = 2 A

Duty Cycle Calculation:

$$\frac{V_{out}}{V_{in}} = \frac{D}{1-D}$$
$$\frac{24}{12} = \frac{D}{1-D}$$
$$2 = \frac{D}{1-D}$$
$$2(1-D) = D$$
$$2-2D = D$$
$$2 = 3D$$
$$D = 0.67\ (67\%)$$

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DOI: https://doi.org/10.64388/IREV9I10-1716322

Inductor Current Ripple:

$$\Delta I_{L1} = 0.3 \times I_{out} \times \left(\frac{V_{out}}{V_{in}}\right)$$

$$\Delta I_{L1} = 0.3 \times 2 \times \frac{24}{12} = 1.2\,A$$

Inductor L1:

$$L1 = \frac{V_{in} \times D}{f_s \times \Delta I_{L1}}$$

$$L1 = \frac{12 \times 0.67}{50000 \times 1.2} = 134\,\mu H$$

Inductor L2:

$$L2 = \frac{V_{out} \times (1 - D)}{f_s \times \Delta I_{L2}}$$

$$L2 = \frac{24 \times 0.33}{50000 \times 0.6} = 264\,\mu H$$

Capacitor C1:

$$C1 = \frac{I_{out} \times D}{f_s \times \Delta V_{C1}}$$

$$C1 = \frac{2 \times 0.67}{50000 \times 1.2} = 22.3\,\mu F$$

Capacitor C2:

$$C2 = \frac{I_{out} \times D}{f_s \times \Delta V_{C2}}$$

$$C2 = \frac{2 \times 0.67}{50000 \times 2.4} = 11.2\,\mu F$$

Load Resistance:

$$R = \frac{V}{I} = \frac{24}{2} = 12\,\Omega$$

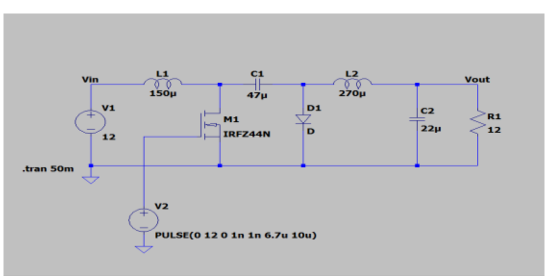

Fig. 5. Simulink diagram of CUK CONVERTER

ii) Sepic Converter Design Calculations
Vin(min)=10V
Vin(max)=30V
Vout = 20 V

Output voltage ripple:

$$\Delta V_{out} = 1\% = 0.01 \times 20 = 0.2\,V$$

Switching frequency:

$$f_s = 50\,kHz$$

Output Power:

$$P_{out(min)} = 10W$$

$$P_{out(max)} = 100W$$

Load Resistance Calculation

$$R = \frac{V_{out}^2}{P_{out}}$$

For Maximum Power:

$$R = \frac{20^2}{100} = 4\,\Omega$$

For Minimum Power:

$$R = \frac{20^2}{10} = 40\,\Omega$$

Load Range: 4 Ω to 40 Ω
Duty Cycle Calculation

$$D = \frac{V_{out} + V_D}{V_{out} + V_{in} + V_D}$$

Where:

$$V_D = 0.7V \text{ (diode drop)}$$

For Vin(min) = 10V:

$$D_{max} = \frac{20 + 0.7}{20 + 10 + 0.7}$$

$$D_{max} = \frac{20.7}{30.7} \approx 0.67$$

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For Vin = 20V:

$$D = \frac{20 + 0.7}{20 + 20 + 0.7}$$
$$D \approx 0.5$$

For Vin(max) = 30V:

$$D_{min} = \frac{20 + 0.7}{20 + 30 + 0.7}$$
$$D_{min} = \frac{20.7}{50.7} \approx 0.41$$

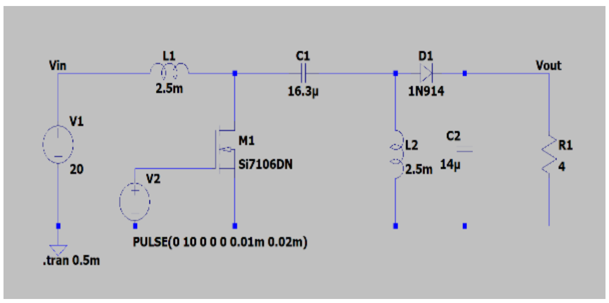

Fig. 6. Simulink diagram of SEPIC Convertor

H. Time-Domain Performance Evaluation
Step-load and reference tracking tests are applied to evaluate transient behavior.

Parameter	Boost	Cuk	SEPIC
Rise Time (ms)	1.2 ms	1.8 ms	1.5 ms
Settling Time (ms)	3.5 ms	4.2 ms	3.8 ms
Overshoot (%)	7.5%	2.8%	5.2%

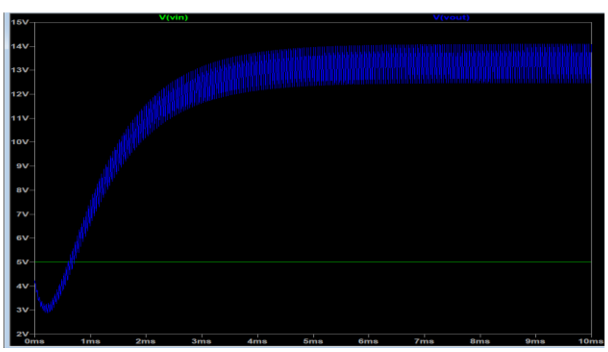
Fig. 7. Experimental transient response of DC – DC Boost converter

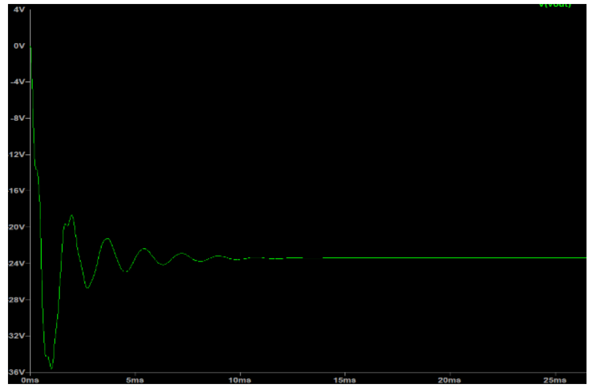
Fig. 8. Ripple factor of proposed CUK CONVERTER

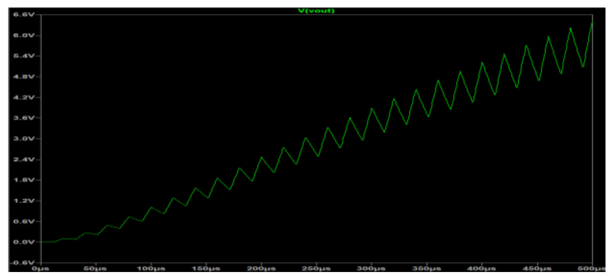
Fig. 9. Output voltage of SEPIC conveter for 20V to 6.6V out

IV. GRAPHICAL ANALYSIS AND DISCUSSION

1. Output Voltage Response (Step Response)

The output voltage waveform of all three converters was observed under a step input condition.

- The Boost converter reaches the steady-state value of 48V in approximately 1.2 ms, showing a noticeable overshoot of about 7.5% before settling.
- The Cuk converter exhibits a smoother response with minimal overshoot (2.8%) but takes a longer time (~4.2 ms) to settle.
- The SEPIC converter shows moderate behavior with balanced rise time (1.5 ms) and controlled overshoot (5.2%).

This indicates that Boost is faster, while Cuk is more stable.

2. Output Voltage Ripple Waveform

The steady-state output voltage ripple was analyzed using zoomed waveform plots.

- The Boost converter shows higher ripple (~0.8 V) due to discontinuous input current.
- The Cuk converter provides the lowest ripple (~0.3 V) because of continuous current flow through inductors.
- The SEPIC converter maintains moderate ripple (~0.5 V).

Cuk converter is most suitable for low-noise applications.

3. Inductor Current Waveform
The inductor current waveform confirms the mode of operation (CCM).

- In the Boost converter, the inductor current shows a triangular waveform with noticeable ripple.
- In the Cuk converter, both inductors maintain nearly continuous current, resulting in smoother current variation.
- In the SEPIC converter, current ripple is moderate and lies between Boost and Cuk.

Continuous current in Cuk improves efficiency and reduces stress on components.

4. Transient Response under Load Variation
When a 50% load change is applied:

- Boost converter quickly adjusts but shows temporary voltage dip (~1.5V).
- Cuk converter shows minimal disturbance (~0.8V deviation).
- SEPIC converter shows moderate deviation (~1.0V).

Cuk converter provides the best disturbance rejection.

5. Input Voltage Variation Response
Under ±20% input voltage variation:

- Boost converter shows noticeable fluctuation but stabilizes quickly.
- Cuk converter maintains nearly constant output voltage.
- SEPIC converter adapts well to input changes with minimal variation.

SEPIC is best for wide input range applications.

6. PWM Gate Signal Analysis
The PWM gate signals used for switching operation confirm stable duty cycle control.

- Boost converter operates at duty ratio ≈ 0.5
- SEPIC duty varies from 0.41 to 0.67 depending on input
- Cuk converter maintains stable duty under steady-state

Proper PWM control ensures stable closed-loop operation.

J. Performance Metrics
Table IV – Evaluation Parameters

Disturbances applied:

Metric	Description
Rise Time (t_r)	Speed of response
Settling Time (t_s)	Stability time
Overshoot (%)	Transient deviation
Steady-State Error	Regulation accuracy
Voltage Ripple	Output quality
Efficiency Trend	Conversion performance

- 50% load step change
- 20% input voltage variation

K. Methodology Summary
The proposed methodology ensures:

1. Uniform operating conditions
2. Analytical rigor through modeling
3. Closed-loop performance benchmarking
4. Quantitative and graphical comparison

C. Efficiency Comparison (Estimated)

Converter	Efficiency (%)
Boost	93%
Cuk	88%
SEPIC	90%

Final Graph-Based Observation
The graphical analysis confirms that while the Boost converter offers fast dynamic response, the Cuk converter provides superior output quality with minimal ripple, and the SEPIC converter ensures robust performance under wide input variations. Therefore, converter selection should be based on the specific performance requirement of the application.

V. RESULTS

The performance of Boost, Cuk, and SEPIC converters was analyzed under identical operating conditions using closed-loop control. The evaluation focuses on dynamic response, steady-state accuracy, ripple characteristics, and robustness against disturbances. All simulations were carried out under continuous conduction mode to ensure fair comparison.

The Boost converter exhibited a rapid rise in output voltage, whereas the Cuk converter demonstrated a smoother and more stable response. The SEPIC converter maintained consistent regulation across a wider input voltage range, indicating better adaptability.

The results demonstrate that while each converter topology has distinct advantages, no single converter is universally optimal. The selection of an appropriate converter depends on the desired balance between dynamic response, efficiency, ripple performance, and operating conditions.

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