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Maximizing Efficiency and Power Quality: A Deep Dive into Hybrid Buck-Boost, Cuk, and SEPIC Converter Topologies

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Abstract

In power electronics, DC-DC converters play a crucial role in industrial power supplies and battery charging. To increase efficiency, simplify design, and enhance power factor, a single-switch hybrid converter integrating SEPIC and Cuk is introduced in this work, along with comparisons of hybrid Buck-Boost, Cuk, and SEPIC topologies. The suggested converters increase efficiency while reducing size, cost, and total harmonic distortion (THD) by eliminating the need for transformers. These hybrids perform better in simulations than traditional designs, making them perfect for low-THD, high-efficiency applications in contemporary power systems. In addition, the safety road to make the load operation with high performance to minimize the overshoot at the starting operation of the converter, by using that technology can reduce that risk.

Keywords: DC-DC converters, hybrid Buck-Boost, Cuk, SEPIC, high-efficiency applications

1. Introduction

The proposed converter is designed to achieve high voltage gain and efficiency while minimizing total harmonic distortion (THD). This is particularly beneficial for applications requiring effective power conversion under varying duty cycles. The combination of SEPIC, Cuk, and buck-boost converters allows for two output voltages of the same magnitude but opposite polarity, making it a versatile solution for modern power supply needs. The paper also presents a Simulink model to simulate the converter's performance, comparing it with traditional SEPIC, Cuk, and buck-boost converters under ideal assumptions. A DC-DC converter, also referred to as a DC converter, is a circuit that converts high-frequency power by using inductors, capacitors, and rapid switching to reduce noise in DC voltage circuits. It can be viewed as the DC equivalent of a continuously variable turn-ratio transformer. Its main application is for stepping up or down the voltage from DC voltage sources [1]. A new method for simple switching dual structures defines two capacitors and two to three diodes. The input voltage can be stepped up using these circuit blocks [2]. Switching DC-DC converters are critical power electronics devices found in a wide range of applications. For years, several well-known single-inductor DC-DC converters, such as Buck, Boost, CSC (Canonical Switching Cell), and buck-boost single inductor converters, as well as well-known two-inductor topologies, Cuk, SEPIC, and Zeta converters, have been studied from various perspectives (voltage gain, operating principle, voltage and current stress, and efficiency) [3][4]. To address the challenges associated with traditional power conversion methods, this research proposes a hybrid bipolar DC-link converter that combines the SEPIC, Cuk, and buck-boost converter configurations. The innovative design incorporates a switched inductor-based gain-enhancing technology, which utilizes two inductors and three diodes. This approach aims to optimize circuit design while reducing costs and meeting the requirements of high-gain applications [5]. The use of an IGBT switch is particularly noteworthy, as it offers superior voltage and power handling capabilities compared to MOSFETs, making it suitable for the voltage stresses encountered during the operation of the combined converters [6].

When selecting a converter for electric vehicles and battery charging, the hybrid bipolar DC-link converter combining SEPIC and Cuk designs is advantageous due to its high voltage gain and efficiency. This converter minimizes output ripple through an input LC filter, ensuring stable performance while reducing overshoot. Implementing a closed-loop control system enhances safety by synchronizing input and output operations, which is crucial for maintaining reliability in varying load conditions. Additionally, using a single IGBT switch simplifies the control structure, mitigating the adverse effects of blocking circuits on the AC power supply.

1.1. Operation and analysis of the novel converters

In this topology, a single switched capacitor network with closed-loop control is introduced, eliminating the need for a transformer and reducing equipment cost and weight. The design consists of a basic single-phase rectifier followed by the switched capacitor network and a high-frequency DC-DC converter used for both the positive and negative cycles. This transformer-less bridge rectifier is expected to achieve higher efficiency by reducing hysteresis and eliminating energy losses typically caused by transformer magnetization.

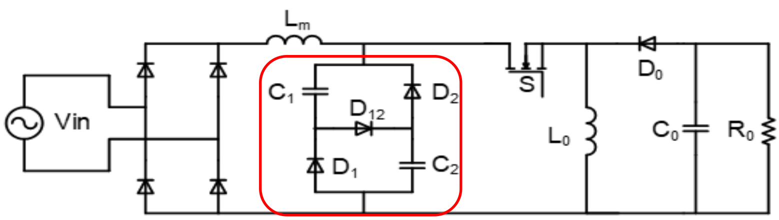


Figure 1. Novel buck-boost converter

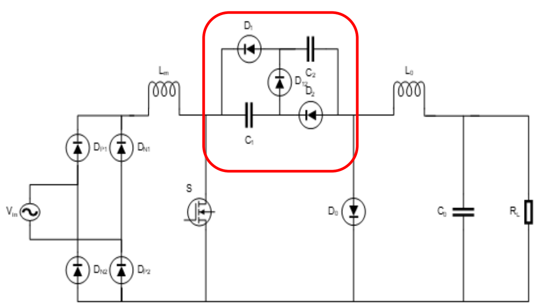


Figure 2. Novel Cuk converter [7]

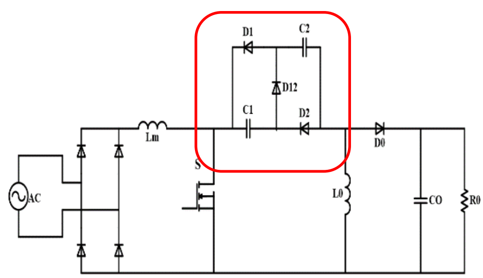


Figure 3. Novel SEPIC Converter [4]

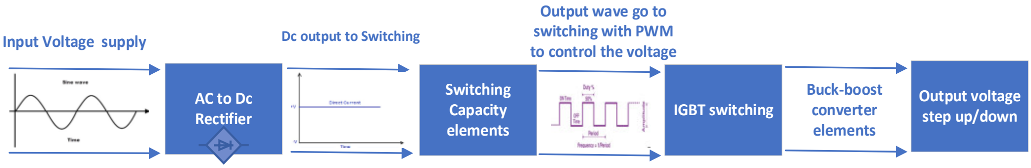


Figure 4. Processing of converters

Table 1. Converters symbols

Symbols	Names
L_m	Input inductance
$C_1 = C_2$	Blocking switch capacitance
L_o	Output inductance
C_o	Output capacitance
R	Output resistance
D	Ideal diode
$Toff$	Time switching during the *off* state
Ton	Time switching during the *on* state

1. →Work operation of the novel buck-boost converter:

During T_{on}, the buck-boost inductor L_0 and output capacitor C_0 are charged by the switched capacitors C_1 and C_2 for a positive half cycle with half of the DC link voltage since these switched capacitors become parallel due to the reverse bias of D_{12} and forward bias of D_1 and D_2. However, during T_{off}, C_1 and C_2 are charged in series with the DC link voltage since D_{12} becomes forward bias. Furthermore, the current in the buck-boost inductor L_0 continues through the freewheeling diode D_0 charges the output capacitor C_0.

Working operation of the novel Cuk converter:

For the topology, during T_{on}, the Cuk inductor L_0 and output capacitor C_0 are charged by the switched capacitors (C_1 and C_2) with half of the DC link voltage since these switched capacitors become parallel due to the reverse bias of D_{12} and forward bias of D_1 and D_2. However, during T_{off}, C_1 and C_2 are charged in series with the DC link voltage since D_{12} becomes forward bias. Furthermore, current in the Cuk inductor L_0 continues through the freewheeling diode D_0 charges the output capacitor C_0.

Working operation of the novel SEPIC converter:

For the topology, during T_{on}, the SEPIC inductor L_0 and C_0 are charged by the switched capacitors (C_1 and C_2) with half of the DC link voltage since these switched capacitors become parallel due to the reverse bias of D_{12} and forward bias of D_1 and D_2. However, during T_{off}, C_1 and C_2 are charged in series with the DC link voltage since D_{12} becomes forward bias. Furthermore, the current in the SEPIC inductor L_0 continues through the freewheeling diode D_0 and charges the output capacitor C_0.

1.2. Voltage gain with duty cycle of the converters

The duty cycle of the switching determines the voltage gain of the three types of DC-DC converters that use switching capacitance while the switching is operating in the *on* and *off* states. Every kind of convertible converter has a different voltage gain, as does the novel voltage gain. The voltage gain is obtained using the driving equations for both the novel converter and the conventional.

1. Novel buck-boost converter.

The voltage gain of the proposed converter can be obtained from the volt-sec balance across inductors over the switching frequency.

The conventional converter,

$$\frac{u_o}{u_{in}} = -\frac{\delta}{(1-\delta)} \tag{1}$$

For the novel converter, the voltage gain will be,

$$\frac{u_o}{u_{in}} = -\frac{\delta}{(1-\delta)(2-\delta)} \tag{2}$$

By comparing (1) and (2), we can see that (2) has an extra term (2 - δ) in the denominator. The term (2 - δ) is greater than 1 whenever the duty cycle is between 0 and 1. This suggests that the recommended converter has a greater step-down capability than the conventional one.

2. Novel Cuk converter.

The same techniques are employed that allow the volt-sec balance across the inductance of the converter in order to drive the equation for the Cuk converter.

The conventional converter,

$$\frac{u_o}{u_{in}} = -\frac{\delta}{(1-\delta)} \tag{3}$$

But after adding the switching capacitors, the novel voltage gain for the Cuk converter,

$$\frac{u_o}{u_{in}} = -\frac{\delta}{2(1-\delta)} \tag{4}$$

Comparing (3) and (4), it can be said that these proposed converters step down two times steeper than that of conventional Cuk converter.

3. Novel Sepic converter.

Regarding the voltage balance sequence passing through the inductance of the converter, the voltage gain will be obtained.

The conventional SEPIC converter,

$$\frac{u_o}{u_{in}} = \frac{\delta}{(1-\delta)} \tag{5}$$

After having added filtering capacitance to the switching the voltage gain of the novel converter,

$$\frac{u_o}{u_{in}} = \frac{\delta}{(1-\delta)(2-\delta)} \tag{6}$$

It is observed that (6) has an additional term (2 - δ)in the denominator by comparing (5) and (6). Whenever the duty-cycle falls between 0 and 1, the term (2 - δ) is greater than 1. This indicates that the suggested converter can step up more than the traditional one.

When comparing the three converters, each one will accept the positive direction of the SEPIC in the same way as it accepts the output direction in terms of voltage for the novel SEPIC and buck-boost.

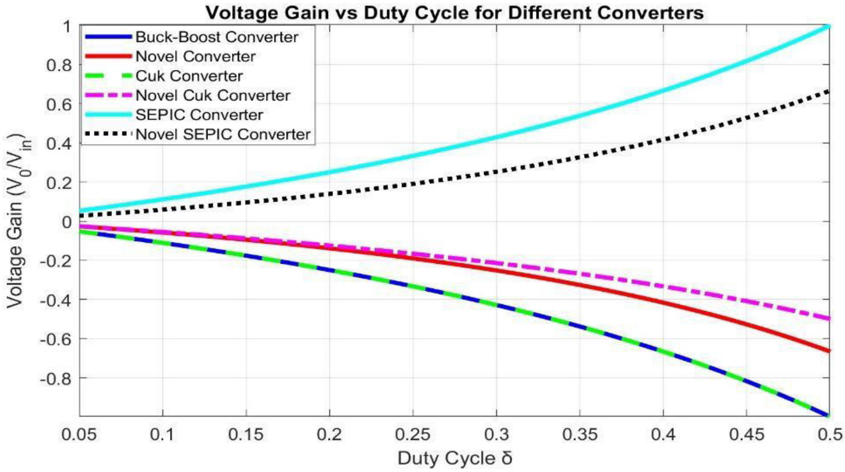


Figure 5. The voltage gain of the difference converter

The voltage gain of six distinct converters is shown as a function of the duty cycle in Figure 5, which also highlights the performance of each converter between 5% and 50% duty cycle. As expected for its step-down function, the buck-boost converter exhibits a negative voltage gain that falls as the duty cycle rises. The new converter performs better thanks to a new term in its equation that causes a slight drop in voltage gain. Both the Cuk and novel Cuk converters show negative gains; however, the output of the novel Cuk converter is more controllable due to its smoother decrease. Both the SEPIC and the novel SEPIC converters exhibit positive voltage gains; however, the novel SEPIC converter's rise is steeper, suggesting that it is capable of greater step-up. In comparison to conventional designs, the new converters improve voltage conversion efficiency overall and offer enhanced control and performance.

1.3. Efficiency Analysis with duty cycle of the converter

As the title of the paper says, the main tasks for those converters are increasing the efficiency of the converters to prepare the decrease in the total losses of the converters that can be used as the supplier for EV charging and many other applications.

1. Novel buck-boost converter and SEPIC converter.

Both converters have the same equations then the efficiency of our proposed converters is expressed as follows,

$$\eta = \frac{\rho_o}{\rho_i} = \frac{u_o}{u_{in}} \frac{(1-\delta)(2-\delta)}{\delta} \tag{7}$$

The efficiency of the conventional buck-boost converter is

$$\eta = \frac{\rho_o}{\rho_i} = \frac{u_o}{u_{in}} \frac{(1-\delta)}{\delta} \tag{8}$$

Comparing (7) and (8), we got,

$$\eta = \eta_C(2-\delta) \tag{9}$$

Since the term (2 - δ) is always greater than 1, the efficiency of our proposed converters is greater than the conventional one for any duty cycle.

2. Novel Cuk converter.

The efficiency of our novel converters is expressed as follows,

$$\eta = \frac{\rho_o}{\rho_i} = \frac{u_o}{u_{in}} \frac{2(1-\delta)}{\delta} \tag{10}$$

Comparing (8) and (10), we got,

$$\eta = \eta_C \cdot 2 \tag{11}$$

Therefore, it is clear that these proposed converters have twice the efficiency of conventional ones for any duty cycle.

2. Output results of the converters

The following assumptions were made to simplify the theoretical analysis.

1. All the components are assumed to be ideal.
2. For the simplification of analysis, |Vin| was considered as a purely rectified sinusoidal source.
3. A Larger value of output capacitor C_0 was considered to refer to u_0 as a pure DC voltage.
4. Both converters have been simulated using PSPICE for the following data specifications.

Table 1. Data of simulation

Converters parameters	Novel buck-boost	Novel Cuk	Novel SEPIC
L_m	$300 \cdot 10^{-6} H$	$300 \cdot 10^{-6} H$	$50 \cdot 10^{-6} H$
$C_1 = C_2$	$500 \cdot 10^{-6} F$	$500 \cdot 10^{-6} F$	$100 \cdot 10^{-6} F$
L_o	$1200 \cdot 10^{-6} H$	$700 \cdot 10^{-6} H$	$3000 \cdot 10^{-6} H$
C_o	$1700 \cdot 10^{-6} F$	$1000 \cdot 10^{-6} F$	$4000 \cdot 10^{-6} F$
R	100Ω	100Ω	100Ω

2.1. Comparison results of novel buck-boost converter

1. Input Power Factor Comparison:

Our proposed topology has a higher power factor than the conventional buck-boost converter as illustrated below. The input inductor L_m, followed by the switched capacitor network, forms an input L-C type filter for each half cycle of operation. This L-C input filter reduces the input current ripple and harmonics. Thus, it improves the input power factor (IPF) in our proposed topology.

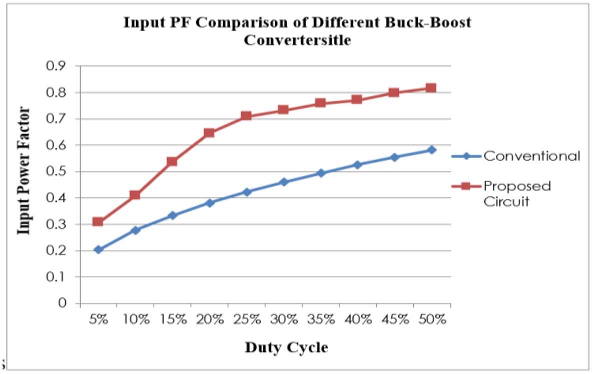


Figure 6. IPF of buck-boost comparison

2. Efficiency and THD Comparison:

Our proposed topology reduces the Total Harmonic Distortion (THD) of the input current compared to the conventional buck-boost converter by introducing an L-C input filter, which utilizes an input inductor and a switched capacitor network, thereby minimizing current ripple. Additionally, the proposed design offers higher efficiency, especially with the single-stage switched capacitor network configuration. The use of transformerless bridge rectifiers reduces hysteresis losses, leading to improved energy efficiency. Mathematically, it has been proven that this topology outperforms the conventional buck-boost converter in terms of both THD reduction and efficiency.

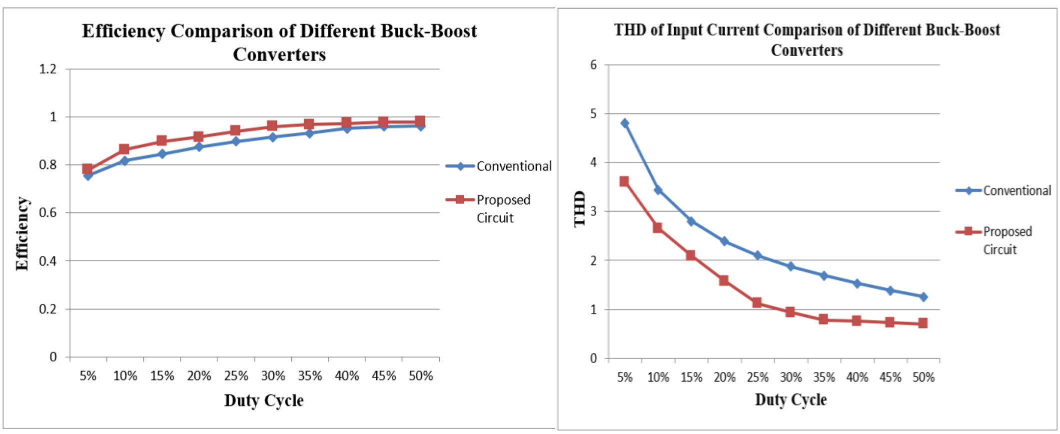


Figure 7. Efficiency and THD of buck-boost converter

2.2. Comparison results of novel Cuk converter

1. Input Power Factor Comparison:

The proposed topology improves the power factor compared to the conventional Cuk converter by using an L-C input filter. This reduces current ripple and harmonics, resulting in a higher power factor.

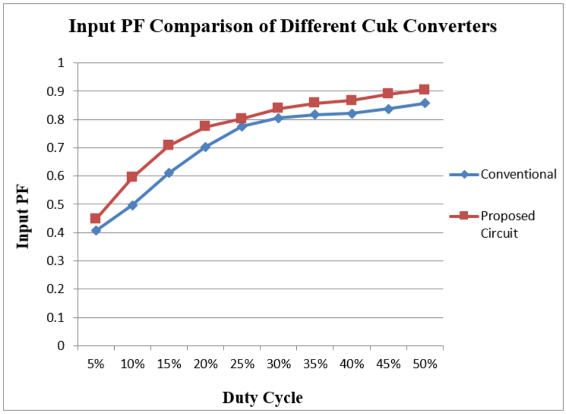
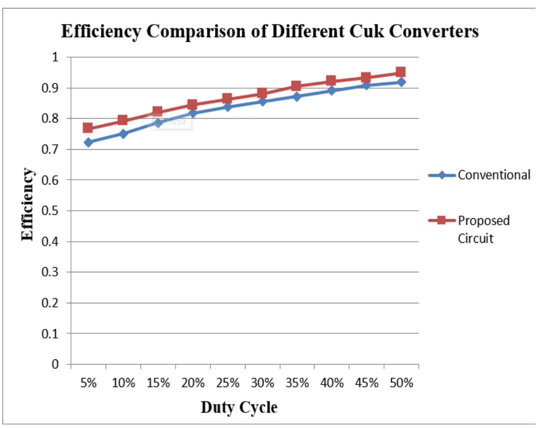


Figure 8. IPF comparison of Converter

2. Efficiency and THD Comparison:

The proposed topology is more efficient than the conventional Cuk converter due to its single-stage switched capacitor network and transformerless bridge rectifier, resulting in reduced energy loss. It also features lower total harmonic distortion (THD), with an L-C input filter that minimizes current ripple.



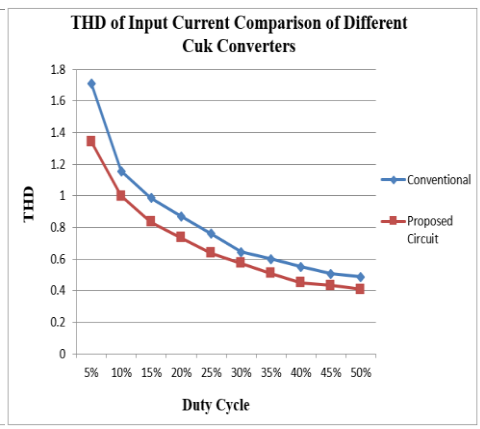


Figure 9. Efficiency and THD of Cuk converter

2.3. Comparison results of novel SEPIC Converter

The proposed topology offers improved performance over the conventional SEPIC converter by providing a higher power factor due to the L-C input filter, which reduces current ripple and harmonics. It also achieves greater efficiency through the use of a single-stage switched capacitor network and transformer-less design, minimizing energy loss and hysteresis. Furthermore, the topology results in lower total harmonic distortion (THD) by reducing input current ripple, making it a more efficient and reliable solution for power conversion.

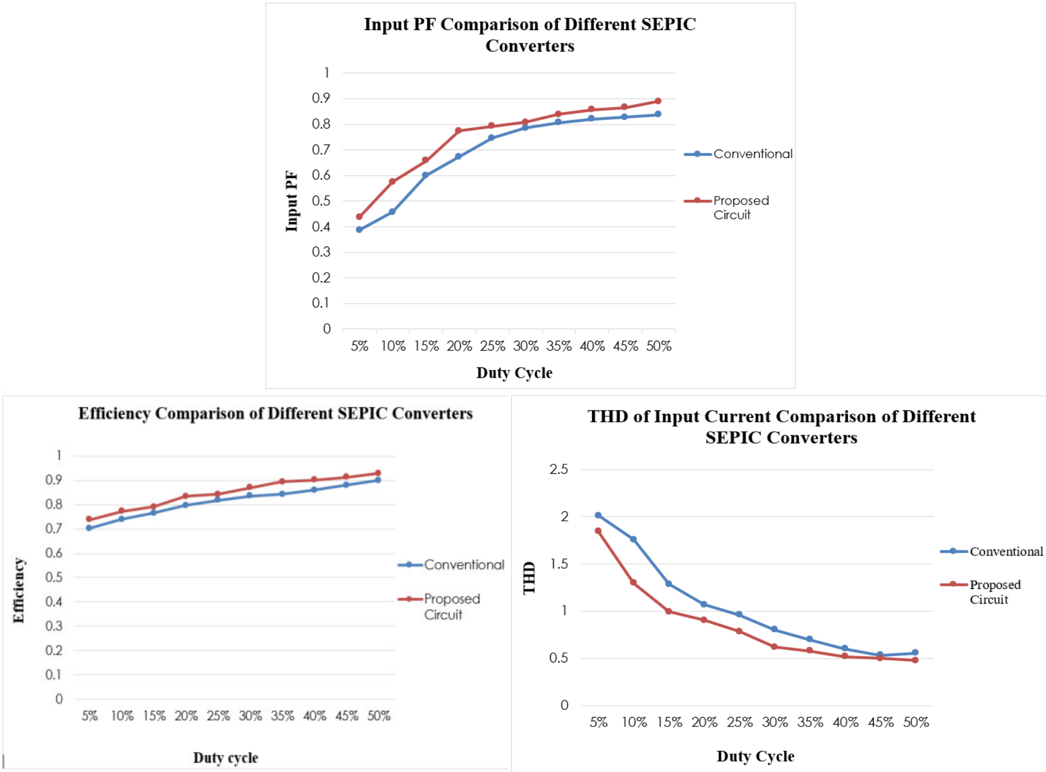


Figure 10. Comparison of SEPIC converter

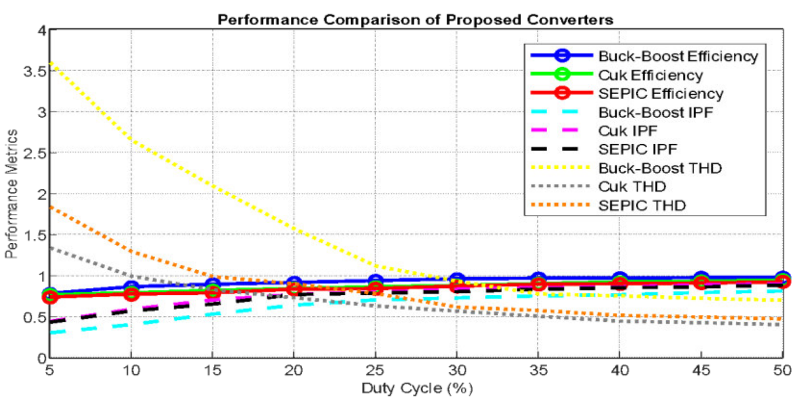


Figure 11. The final performance

3. Conclusion

The novel converters, including buck-boost, Cuk, and SEPIC demonstrate significant improvements in efficiency, Input Power Factor (IPF), and Total Harmonic Distortion (THD) compared to conventional designs, making them suitable for electric vehicle (EV) charging applications. The Buck-Boost converter achieves the highest efficiency (0.9781), while the Cuk converter boasts the best IPF (0.9047) and lowest THD (0.4070), indicating superior power quality. These enhancements, particularly in capacitance switching performance, enable better handling of dynamic loads, ensuring optimal energy transfer, reduced harmonics, and improved safety, thereby facilitating the transition to sustainable transportation solutions.

4. References

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