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Analysis of different converter topologies for EV applications

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ABSTRACT

Electric vehicles (EVs) are gaining global prominence due to their high efficiency, low noise, and minimal carbon emissions. A critical aspect of EV performance lies in the interaction between energy storage systems (ESS) and power converters. Nonetheless, power delivery from storage units tends to be unreliable and needs strong converter units for effective and stable energy transmission. Several forms of direct current-to-direct current conversion systems used in electric vehicles are thoroughly examined in the paper, including both isolated and non-isolated designs such as those with the cuk, flyback, and push-pull architectures. The paper looks at converter categorization, control methods such as proportional-integral and artificial neural networks, as well as the method of modulation using unipolar and bipolar sinusoidal pulse-width modulation (PWM). Additionally, the role of optimization algorithms in improving converter performance is explored. Simulations were conducted using MATLAB/Simulink to evaluate each topology under varying load and input voltage conditions. The results demonstrate that the Push-Pull converter has the best efficiency for high-power applications, while the Cuk and Flyback converters are best for applications requiring continuous current and low-power, compact designs, respectively. This research offers insights for choosing optimal converter structures to improve energy efficiency and reliability of systems in electric vehicles.

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1. INTRODUCTION

Growing concern regarding global warming and climate change has caused the world to shift towards electric vehicles (EVs) from internal combustion engine (ICE) vehicles. Transport contributes significantly to environmental degradation with nearly 24–27% of the world's carbon dioxide (CO_2) emissions [1], [2]. Most of these emissions result directly from the burning of fuel [3]. EVs present a more sustainable option by virtue of their efficiency, low operating noise levels, low emissions, and lowered fossil fuel dependence [4], [5].

Although they offer advantages, EVs have significant technical issues, particularly in the engineering and operation of power conversion and energy storage systems. The power provided from the batteries is intrinsically varying and must be conditioned by high-power electronic converters in order to make a vehicle perform as desired [6], [7]. In electric vehicles (EV), typically an energy transfer mechanism involves DC-DC converters for regulating both voltage and current levels between the energy storage system (ESS) and the Motor [8], [9]. Operating loads, temperature restrictions, duty ratio, and variations in input voltage levels must all be taken into account by the conversion scheme [10], [11].

Converter topologies for EV applications are, in general, categorized into non-isolated (e.g., bidirectional DC-DC and Cuk) and isolated (e.g., flyback, push-pull, and resonant) types [12], [13]. Non-isolated converters are small and efficient for medium to high power levels, whereas isolated converters offer galvanic isolation, which is required for safety and voltage multiplication [14]-[16]. Topologies such as the Cuk converter deliver continuous input and output current with less ripple and are hence well-suited for sensitive loads [17]. Flyback converters are cost-effective and used in low-power applications since they possess a high voltage gain and simplicity [18], [19].

Push-Pull converters, however, are transformer-based isolated topologies with high power transfer efficiency but stringent switching control to avoid short circuits and simultaneous conduction [20], [21]. Furthermore, it has been suggested that DC-DC converters' dynamic response and stability be enhanced by the application of control strategies like proportional-integral control, model predictive control, and artificial neural networks [22], [23]. Additionally, techniques like soft-switching and particle swarm optimization have been thoroughly researched for improving performance, reducing switch losses, and managing electromagnetic disturbances in power electronics systems [24], [25]. In order to compare different configurations such as the cuk, flyback, and push-pull converters across a range of loads and voltages, this study plans to perform extensive simulations. Electrical vehicle performance metrics, including output voltages, currents, and powers, are analyzed using the MATLAB/Simulink tool to find the best topologies for enhancing energy efficiency and system stability.

2. METHOD

This study examines the feasibility of using three DC-DC converter topologies: cuk, flyback, and push-pull in EV settings. The simulation and modeling of these converters are performed in MATLAB/Simulink under various load conditions and voltage levels at the input side. According to isolation type, converters are classified as non-isolated (cuk) and isolated (flyback and push-pull).

2.1. Converter classification

The DC-to-DC converters employed in EVs are generally classified as:

- Non-isolated converters are typically utilized for high and medium power applications. These converters lack galvanic isolation from input to output but provide high compactness and efficiency. Examples are traditional bidirectional DC to DC converters, interleaved converters, and Cuk converters.
- Isolated converters use transformers for electrical isolation and are best used for low to medium-power applications. Some of the examples are Flyback, Push-Pull, and Resonant converters.

The taxonomy of EV converters into isolated and non-isolated converters is shown in Figure 1.

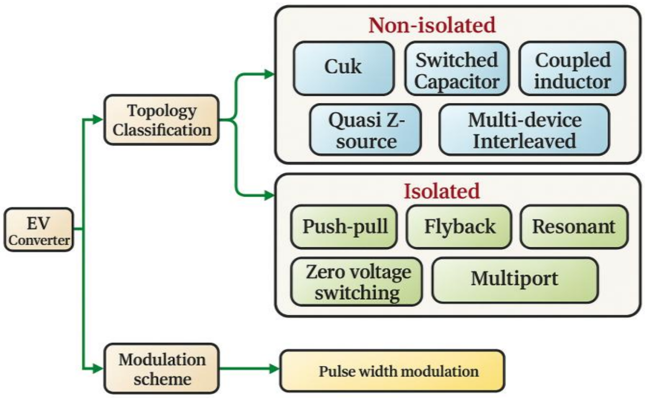

Figure 1. EV converters classification

2.2. Cuk converter (non-isolated)

The Cuk converter both steps down and steps up voltage. It transfers energy through a coupling capacitor and uses one magnetic core, offering continuous current at output and input with lower ripple. The converter is in continuous conduction mode (CCM), improving the dynamic response as well as reducing noise. The MATLAB/Simulink model was developed with the following parameters:

- Input voltages: 30 V, 40 V, and 50 V
- Load types: resistive (R), resistive-inductive (RL), resistive-inductive-capacitive (RLC), and open circuit (OC)
- Switching frequency: 20 kHz
- LC filters: properly sized to ensure continuous conduction mode

The relationship between output voltage and input voltage in the cuk converter is given by (1).

$$V_o = V_i \left(\frac{-D}{1-D}\right) \tag{1}$$

Where V_o is the output voltage, V_i is the input voltage and D is the duty cycle. The negative sign indicates polarity inversion between input and output. The simulated circuit of the Cuk converter is shown in Figure 2.

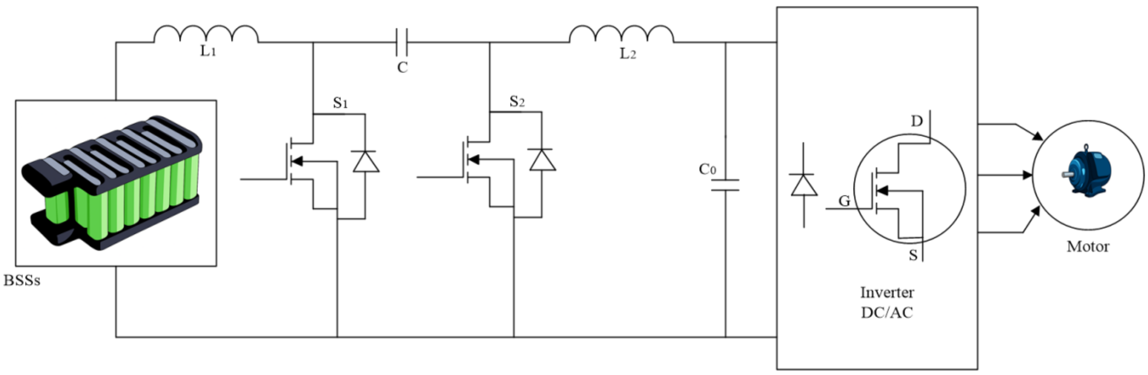

Figure 2. Cuk converter

2.3. Flyback converter (isolated)

The Flyback converter is an isolated topology derived from the buck-boost converter. It stores energy in the transformer's magnetizing inductance during the ON state of the switch and transfers it to the output during the OFF state. It is widely used for its simple structure and cost-effectiveness.
Simulation parameters included:

- Transformer turn ratio $\frac{N_2}{N_1} = 2$
- Magnetizing inductance LmL_mLm: tuned to control ripple
- Switching frequency: 20 kHz
- Load types: R, RL, RLC, and OC
- Duty cycle D: varied for performance testing

The magnetizing current I_L during OFF-time is given by (2):

$$I_L = \frac{-V_0(1-D)T}{L_m} \cdot \frac{N_1}{N_2} \tag{2}$$

Where T is the switching period, L_m is the magnetizing inductance, and N_1, N_2 are the primary and secondary winding turns. The circuit configuration of the Flyback converter is shown in Figure 3.

2.4. Push-Pull converter (isolated)

The Push-Pull converter uses a center-tapped transformer and two switches to alternately transfer energy from the primary side to the secondary. This provides bidirectional energy transfer and good voltage gain, though with careful switching to prevent short-circuit paths. Simulation settings included:

- Input voltages: 30 V, 40 V, and 50 V

– Transformer turn ratio: 1:2
– Load types: R, RL, RLC, and OC
– Switching control: non-overlapping gate signals to prevent simultaneous conduction
– Output filter: LC filter to smooth output waveform

The voltage gain of a Push-Pull converter is defined in (3).

$$\frac{V_{out}}{V_{in}} = nD \tag{3}$$

With n being the transformer turn ratio, V_o the output voltage, V_i the input voltage and D the duty cycle. The simulated Push-Pull converter circuit is given by Figure 4.

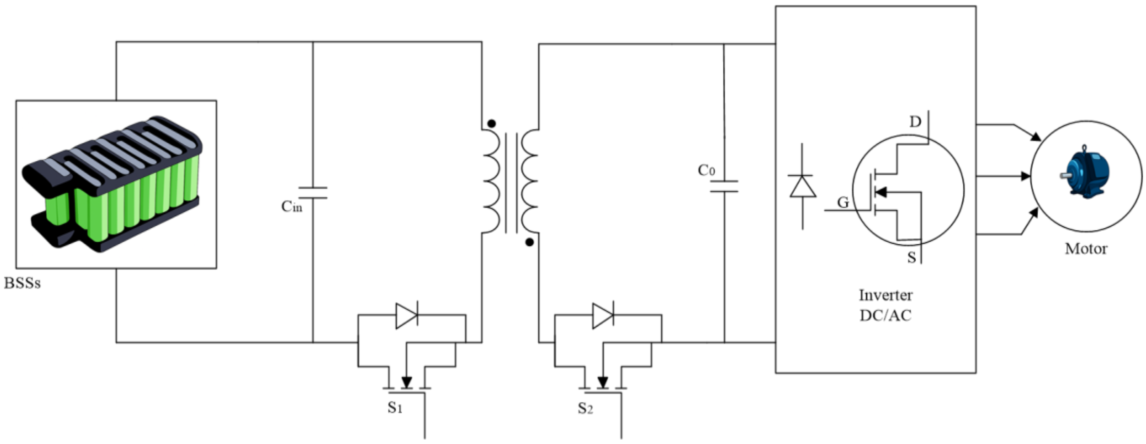

Figure 3. Flyback converter

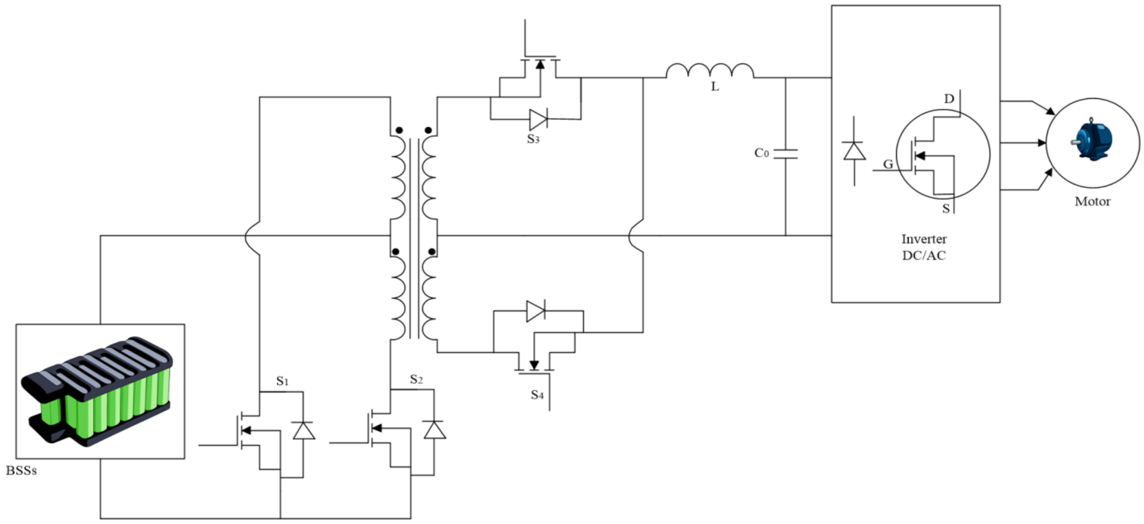

Figure 4. Push-pull converter

3. RESULTS AND DISCUSSION

To compare the performance of the three converter topologies, each of the models was simulated on MATLAB/Simulink for the same input voltages (30 V, 40 V, and 50 V) with different load conditions (resistive, RL, RLC, and open circuit). The output is shown in terms of input/output voltage, current, and power waveforms, and also quantitative data tables for comparison.

3.1. Cuk converter performance

The cuk converter model showed the ability to offer a negative output voltage under all operating conditions, showing its inherent buck-boost nature. The Simulink model of the cuk converter is illustrated in Figure 5. Input voltage, output voltage, output current, and output power waveforms are illustrated in Figures 6 to 9, respectively.

As noted from Table 1, the converter performed stably under resistive and RL loads, with a highest output power of 219 W at 50 V input with RL loading. For RLC and open-circuit load conditions, the output power was very small or zero as a result of load demand discontinuity. The output confirms that the cuk converter can deliver continuous and smooth current, though its efficiency is marginally affected by increased component stress and higher switching losses.

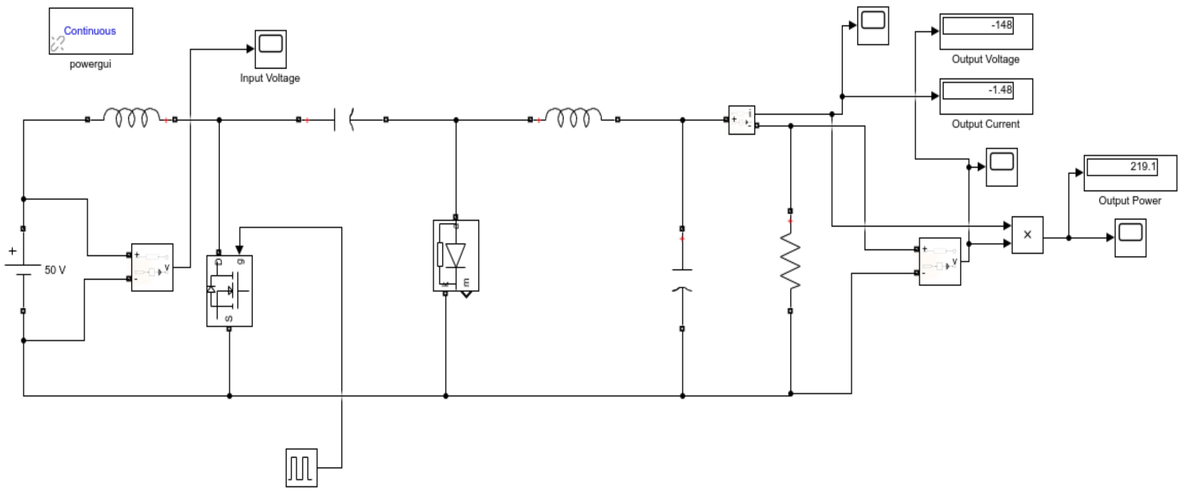

Figure 5. Simulink model of cuk converter

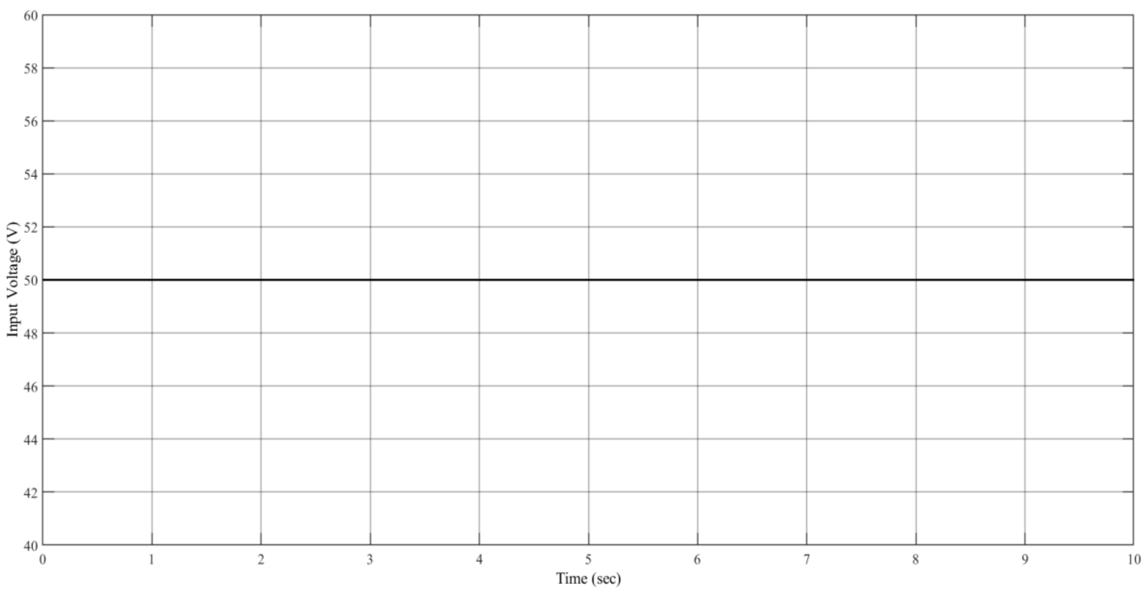

Figure 6. Input voltage waveform of the cuk converter

Table 1. Output readings of Cuk converter at different load conditions

Load	Input voltage = 30 V			Input voltage = 40 V			Input voltage = 50V		
	V_O (V)	I_O (A)	P_O (W)	V_O (V)	I_O (A)	P_O (W)	V_O (V)	I_O (A)	P_O (W)
R	-88.19	-0.8819	77.78	-117.9	-1.179	138.9	-147.5	-1.475	217.6
RL	-88.48	-0.8851	78.31	-117.9	-1.179	138.9	-148	-1.48	219
RLC	-178.9	-0.001193	0.2134	-239	-0.00159	0.3801	-299.1	-0.001988	0.5947
OC	-180.5	0	0	-241	0	0	-301.7	0	0

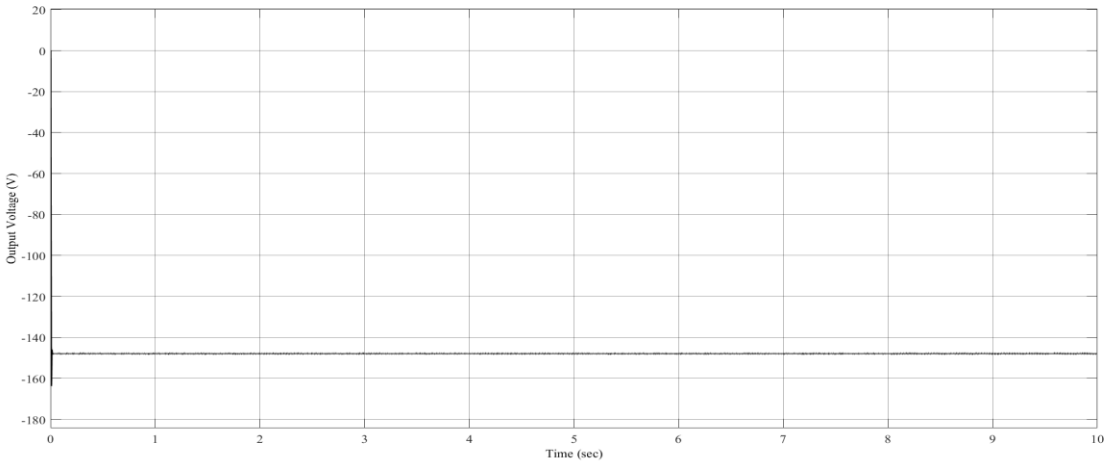

Figure 7. Output voltage waveform of Cuk converter

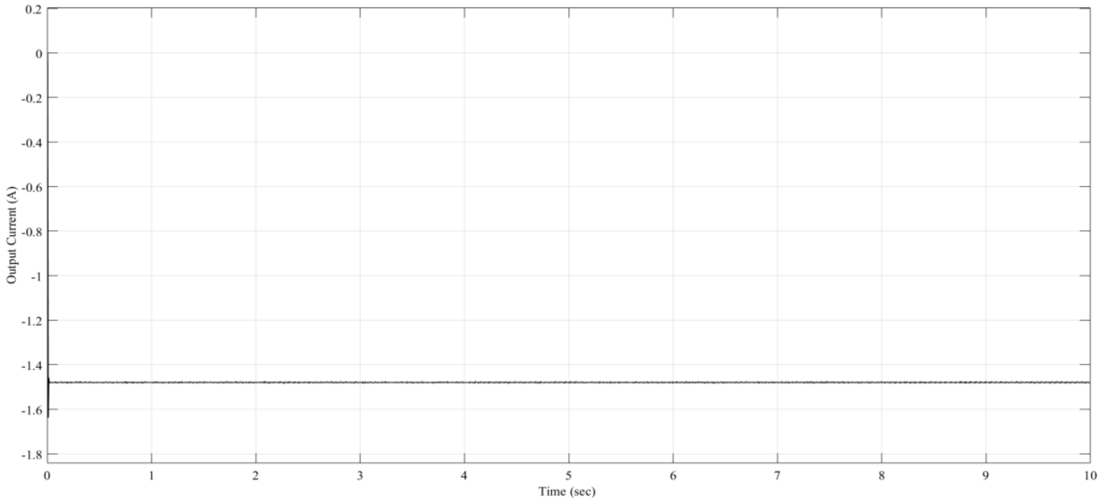

Figure 8. Output current waveform of Cuk converter

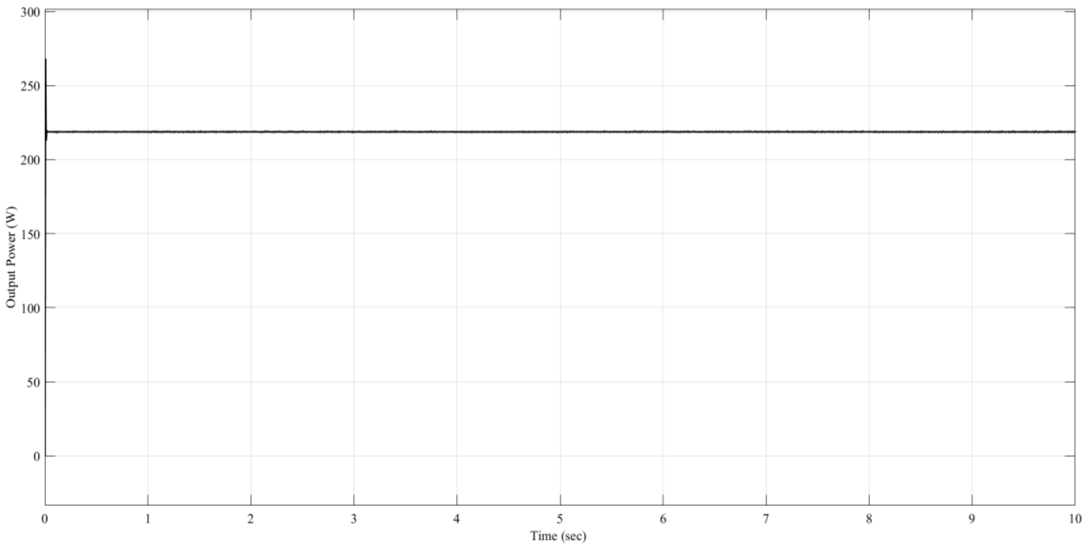

Figure 9. Output power waveform of the cuk converter

3.2. Flyback converter performance

The Flyback converter model, Figure 10, was also tested under the same conditions. Input voltage and output response are recorded in Figures 11 to 14. The converter exhibited high voltage gain, particularly under RL loading.

As indicated in Table 2, the Flyback converter delivered a peak output power of 384.4 W for an input voltage of 50 V under RL load conditions. The converter had good voltage regulation and transformer utilization. Non-ideal high ripple and magnetizing current fluctuations were, however, noticed under specific conditions. Performance was poor under RLC loads as a result of the resonant load nature and poor energy transfer during short conduction periods.

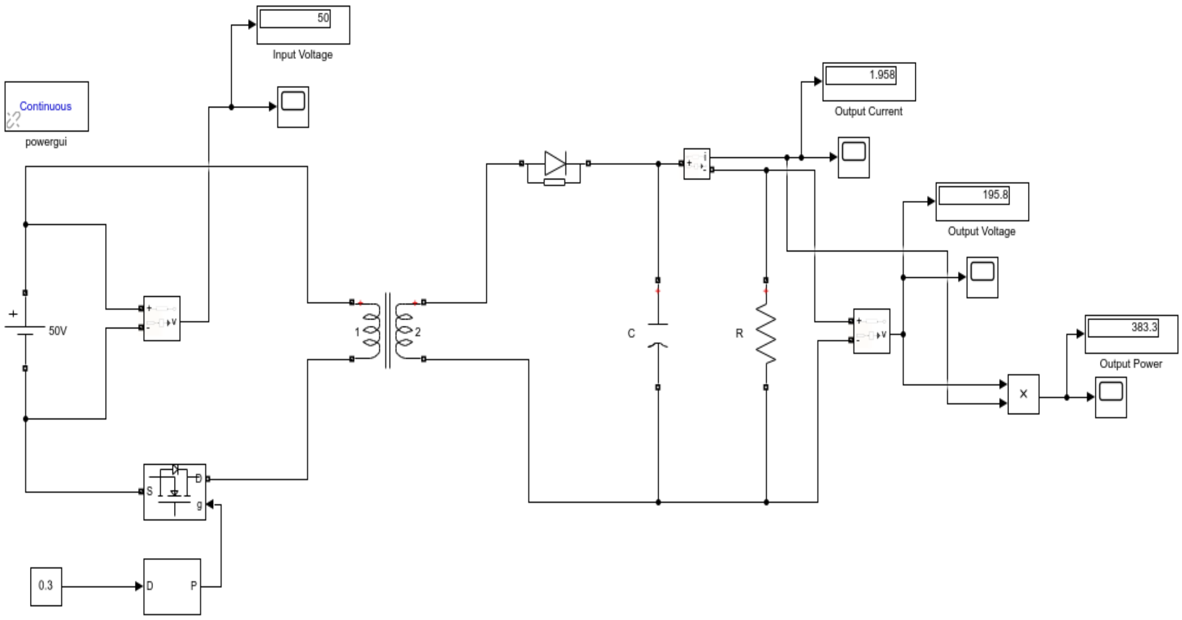

Figure 10. Simulink model of flyback converter

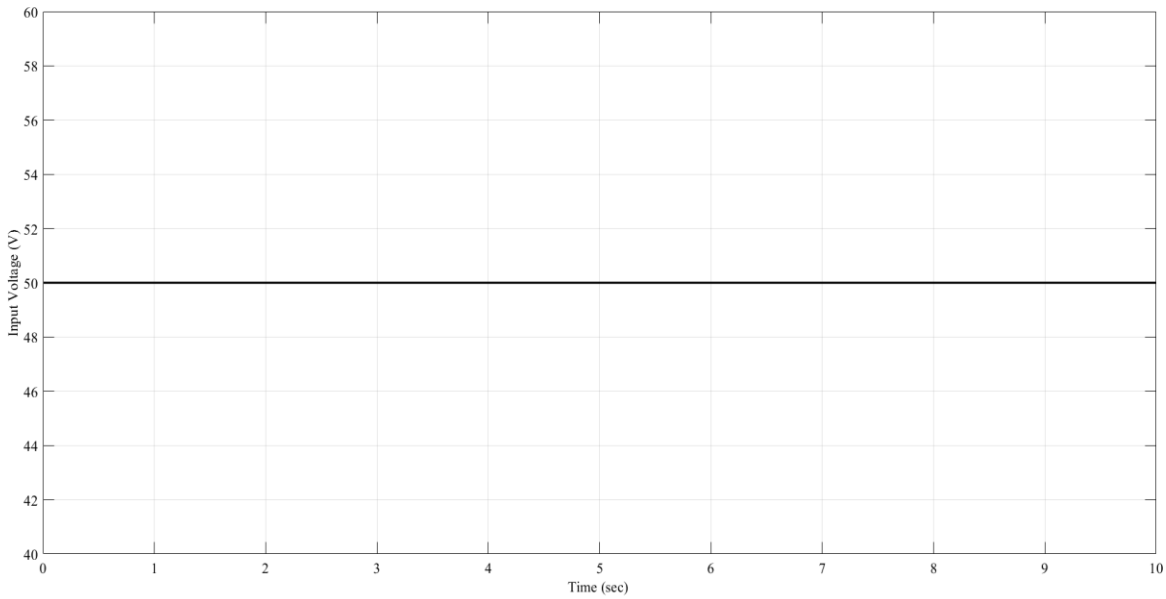

Figure 11. Input voltage waveform of the flyback converter

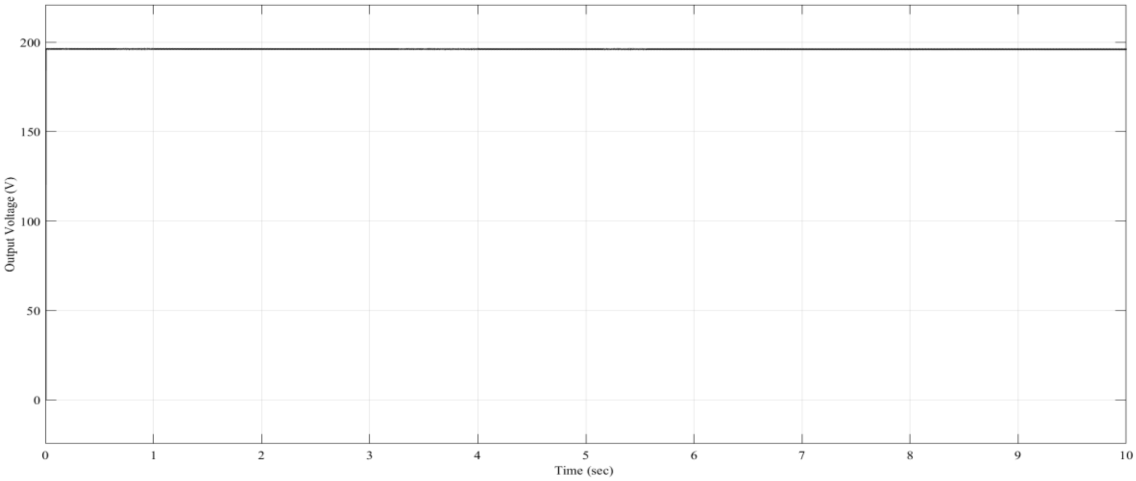

Figure 12. Output voltage waveform of flyback converter

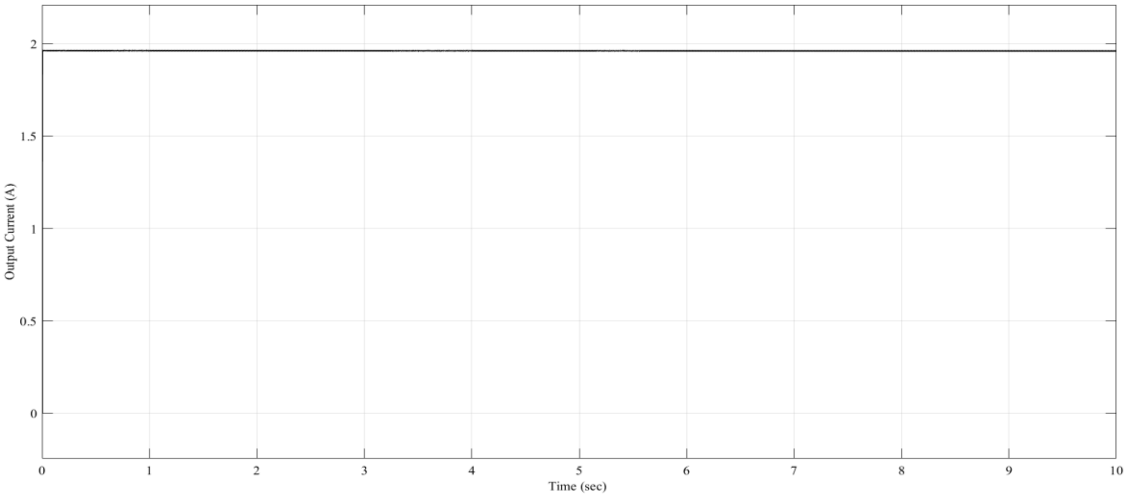

Figure 13. Output current waveform of flyback converter

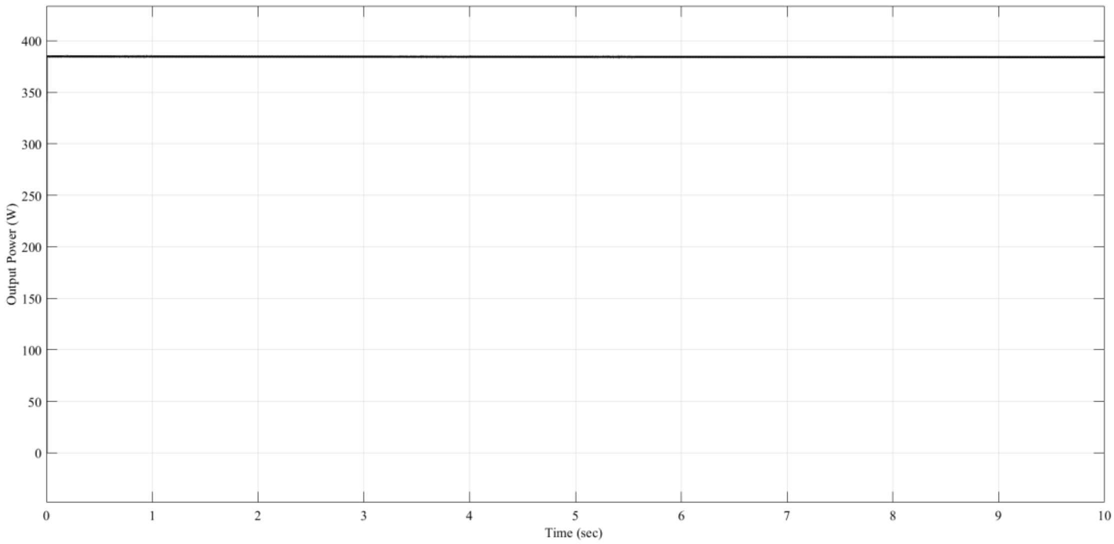

Figure 14. Output power waveform of flyback converter

Table 2. Output readings of fly back converter at varying load conditions

Load	Input voltage = 30 V			Input voltage = 40 V			Input voltage = 50 V		
	V_O (V)	I_O (A)	P_O (W)	V_O (V)	I_O (A)	P_O (W)	V_O (V)	I_O (A)	P_O (W)
R	117.3	1.173	137.5	156.6	1.566	245.3	196	1.96	384
RL	117.3	1.174	137.7	156.8	1.568	245.6	196	1.962	384.4
RLC	124.2	$-1.647*10^{-8}$	$-2.079*10^{-6}$	165.9	$-3.6*10^{-8}$	$-5.9*10^{-6}$	207.5	$-4.9*10^{-8}$	$-1.02*10^{-5}$
OC	124.2	0	0	165.9	0	0	207.5	0	0

3.3. Push-pull converter performance

The push-pull converter, shown in Figure 15, is assessed based on its voltage and current waveforms in Figures 16 to 19. Although the converter provides galvanic isolation and symmetrical power transfer through the transformer, its performance was comparatively lower than the other topologies. It is evident from Table 3 that the converter, even at maximum power of just 2.79 W, produced under 50 V input with RL load, indicated its inadequacy for high-power devices. It also performed poorly under open-circuit and RLC conditions. Nevertheless, it maintained stable waveform performance and less ripple at the output, which can be useful in low-power or signal-sensitive EV subsystems.

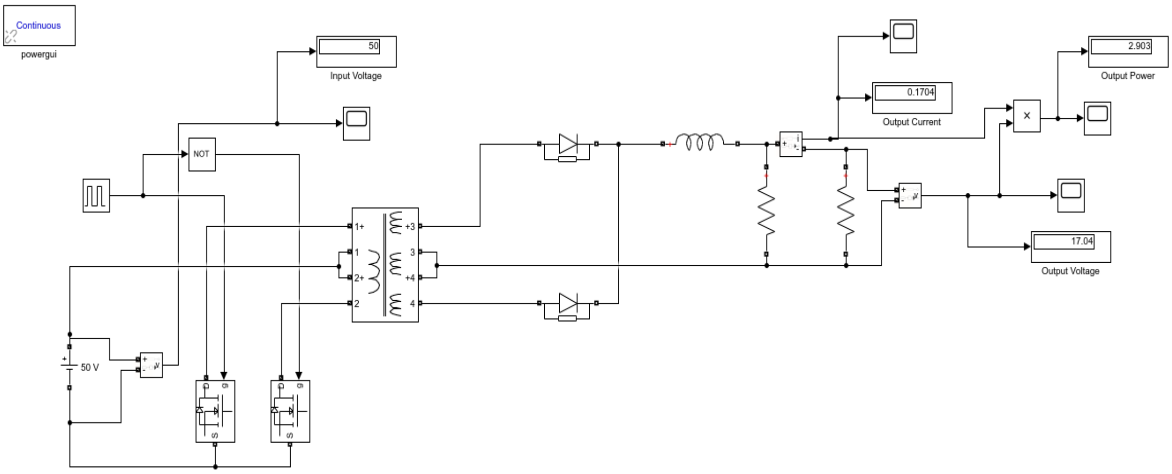

Figure 15. Simulink model of push-pull converter

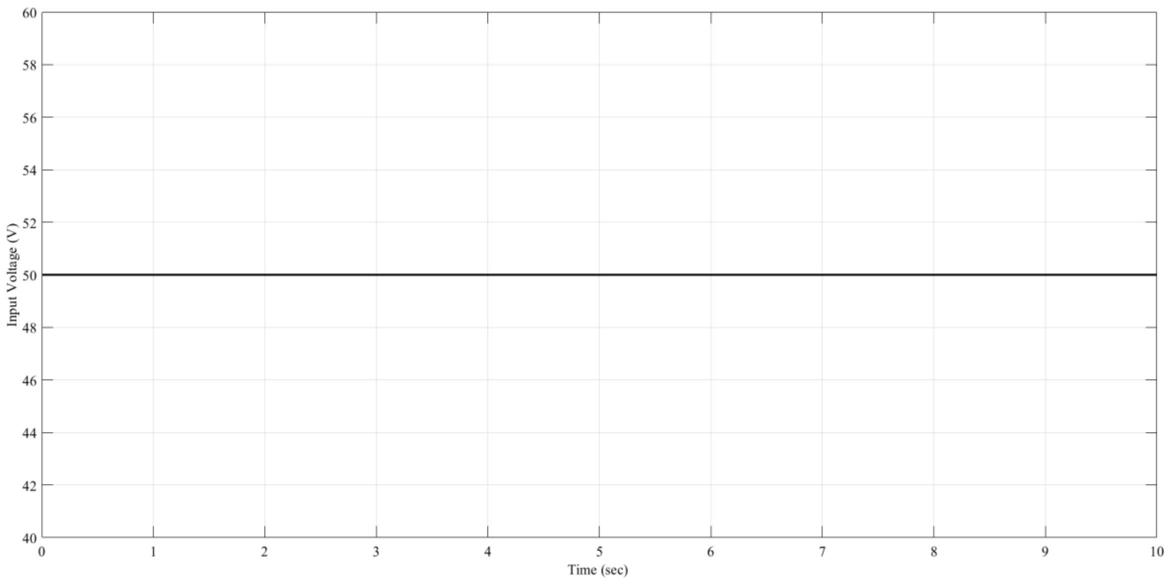

Figure 16. Input voltage waveform of push-pull converter

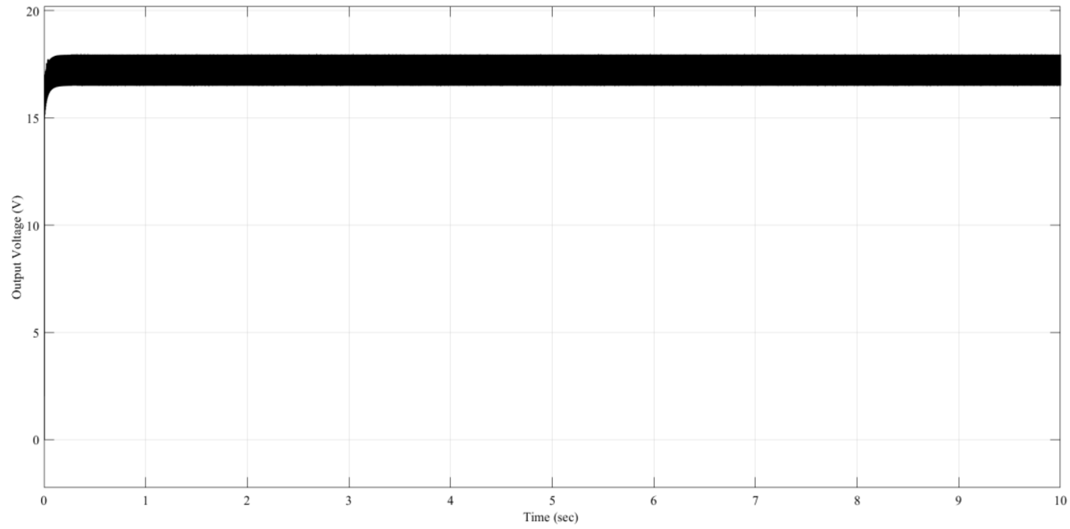

Figure 17. Output voltage waveform of push-pull converter

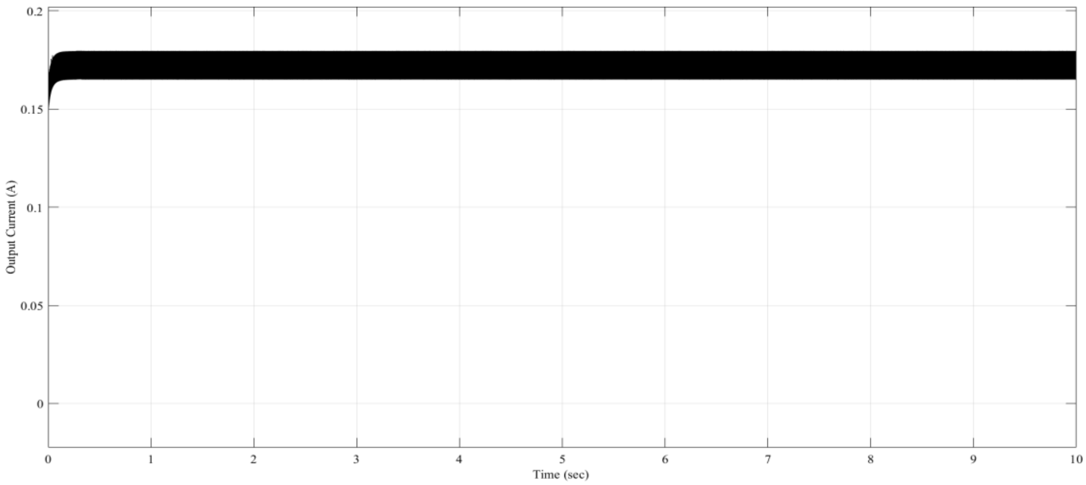

Figure 18. Output current waveform of push-pull converter

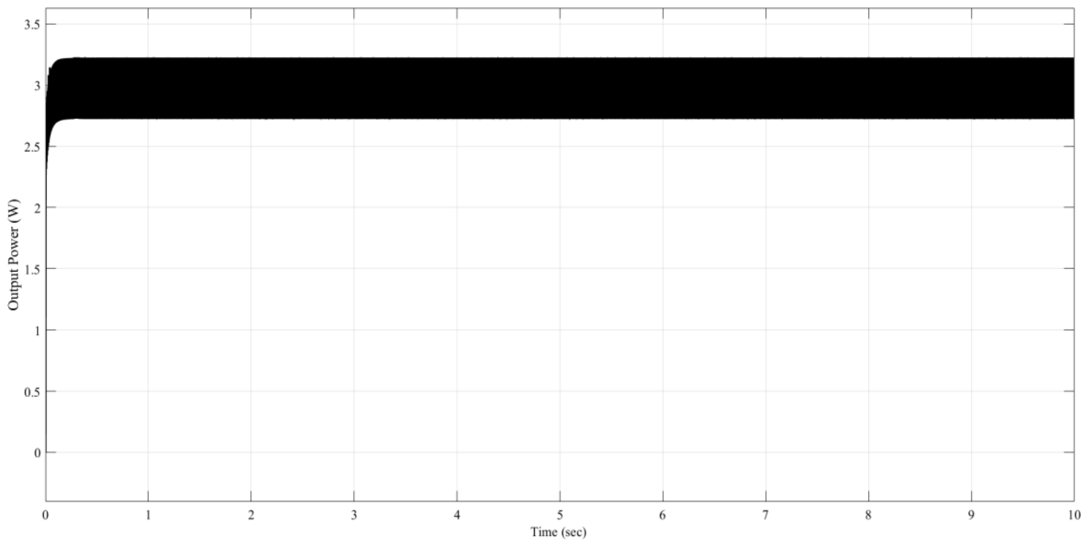

Figure 19. Output power waveform of push-pull converter

Table 3. Output readings of push pull converter for various load conditions

LOAD	Input voltage = 30 V			Input voltage = 40 V			Input voltage = 50 V		
	V_O (V)	I_O (A)	P_O (W)	V_O (V)	I_O (A)	P_O (W)	V_O (V)	I_O (A)	P_O (W)
R	9.698	0.09698	0.940	13.2	0.132	1.742	17.04	0.1704	2.903
RL	9.698	0.09698	0.940	13.2	0.132	1.742	16.7	0.1731	2.891
RLC	14.62	$-2.1*10^{-17}$	$-2.95*10^{-16}$	19.9	$-5.54*10^{-17}$	$-1.1*10^{-15}$	25.17	$-8.37*10^{-17}$	$-2.1*10^{-15}$
OC	10.42	0	0	14.17	0	0	17.93	0	0

3.4. Comparative analysis

The following observations concerning output power and efficiency can be had by comparing Tables 1 to 3:

- Flyback converter: The maximum output power of 384.4 W was demonstrated by the flyback converter for a 50 V input with an RL load (with an estimated efficiency around 85%). It demonstrated good voltage regulation and operated reliably under all loads. Because of leakage in the transformer and switch transitions, there was a noticeable current ripple. Low to moderate power EV systems, where cost reduction and minimization are important factors, are best suited for this converter.
- Cuk converter: When coupled with a resistive load and a 50 V input, the Cuk converter produced a maximum output power of 219 W and had an efficiency of roughly 93%. For applications requiring smooth energy transfer, it made it possible for a constant current flow to occur at both the input and the output. However, this design used more passive components and increased the strain on the switches. It performs admirably in electric vehicles' medium-power components that must run without voltage swings.
- Push-pull converter: When tested under the same voltage and load conditions, the push-pull converter had the lowest maximum output power of 2.891 W, despite having galvanic isolation and operating symmetrically. Due primarily to switching losses and poor use of the transformer core under non-ideal loads, its efficiency was estimated to be between 70 and 75%. This design is more appropriate for low-power components in electric vehicles where transformer isolation is a primary concern, despite its robust and long-lasting structure.

In summary: i) Flyback converter: Highest power output, ~85% efficiency; ii) Cuk converter: Balanced output, ~93% efficiency; and iii) Push-Pull converter: Low output, ~70–75% efficiency. According to these findings, the Push-Pull converter can be used in situations where transformer-based isolation is required but low power output is acceptable. The flyback converter is best suited for cost-sensitive high-voltage gain applications, and the Cuk converter is best suited for continuous current systems.

4. CONCLUSION

Three different DC to DC converter types: cuk, flyback, and push-pull for use in electric vehicles are compared and examined in this project. MATLAB/Simulink and practical tests with various input voltages and loads were used to test each converter. Important parameters like output voltage, current, power transfer, and efficiency were used to gauge their performance.

The findings demonstrated that, with an estimated efficiency of roughly 85%, the Flyback converter can generate up to 384.4 W when the input voltage is 50 V, and the load is of the RL type. Because of this, it's a good choice for electric cars that don't need a lot of power but still need high voltage gain and electrical isolation. Overall, the Cuk converter did well, providing steady, smooth current with a peak efficiency of about 93%. It works best in medium power applications where a smooth, clean energy transfer is crucial. With an efficiency of 70% to 75%, the Push-Pull converter produced the least amount of power. Its lower power output restricts its use to auxiliary or low-power components of electric vehicles, even though it provides electrical isolation through a transformer.

In summary, the study demonstrates that the power requirements and isolation specifications of the electric vehicle system determine which converter is best. The Flyback converter is well-suited to small, isolated applications. The Cuk converter offers superior energy continuity and efficiency for mid-range applications and the Push-Pull converter serves well in situations where isolation is required, but power demands are minimal. These insights can support powertrain engineers and researchers in optimizing converter designs for enhanced energy efficiency and system reliability in electric vehicle platforms.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article.

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