Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 46 No. 3 (2025)

Performance Evaluation of KY Converter for Battery Management Systems in Electric Vehicles

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Abstract:-The performance and reliability of electric vehicles (EVs) heavily depend on the efficiency of their Battery Management Systems (BMS), where DC-DC converters play a vital role in ensuring regulated power flow between the battery pack and the load. Among various converter topologies, the KY converter emerges as a promising solution due to its unique capability of delivering non-pulsating output current, high efficiency, and low output voltage ripple. This paper presents a comprehensive performance analysis of the KY converter compared to conventional buck, boost, and buck-boost topologies under different EV operating scenarios. Through simulation and hardware-level validation, the KY converter demonstrates superior transient response, thermal stability, and reduced electromagnetic interference (EMI), making it highly suitable for integration in EV BMS. Additionally, its simple control architecture enables easier implementation while maintaining consistent performance under varying load and input conditions. The findings indicate that the KY converter is a highly effective and reliable power management component for modern electric vehicle systems.

Keywords*: EV battery management, power converters, KY converter, energy optimization, converter performance, voltage control, thermal stability, EMI reduction, DC-DC conversion.*

1. Introduction

The increasing adoption of electric vehicles (EVs) has intensified the demand for sophisticated and efficient energy management systems. EVs provide an environmentally friendly alternative to conventional internal combustion engine vehicles by utilizing electricity stored in high-capacity batteries. Central to the effective operation of these batteries is the battery management system (BMS), which plays a critical role in ensuring battery safety, optimizing performance, and extending battery lifespan. A robust BMS continuously monitors crucial parameters such as voltage, current, temperature, and state of charge (SOC), while also managing power flow via converters to accommodate the dynamic energy requirements of the vehicle.

Among various power converters, buck converters are commonly used in EVs for voltage step-down applications due to their straightforward design and cost-effectiveness, although they tend to produce significant output voltage ripple and electromagnetic interference (EMI) [1][2]. Conversely, boost converters are employed to increase voltage levels where necessary but may also introduce similar ripple and EMI challenges [3][4]. Buck-boost converters combine the functionality of both buck and boost types, enabling flexible voltage regulation for fluctuating input conditions, though they share the drawback of output ripple and EMI [5][6].

Ćuk converters provide a unique benefit of non-inverting output voltage alongside continuous input and output currents, making them suitable for applications demanding smooth current profiles, albeit at the expense of increased circuit complexity and component count [7][8]. Similarly, Single-Ended Primary Inductor Converters (SEPIC) offer non-inverting output with the ability to both raise and lower voltage levels, catering to scenarios requiring steady voltage outputs, though their efficiency and complexity may vary [9][10].

Bidirectional converter topologies such as Dual Active Bridge (DAB) converters enable power flow in both directions, boasting high efficiency and soft-switching capabilities but often necessitating complex control schemes and facing high voltage stress on switching elements [11][12]. LLC resonant converters are notable for their soft-switching features and excellent efficiency in high-power contexts, making them well-suited for EV applications prioritizing reduced EMI; however, their performance can be sensitive to load fluctuations [13][14].

Integrated multiport bidirectional converters provide the versatility to interface multiple energy sources and storage units, supporting advanced hybrid energy management systems, though they come with intricate design and control challenges [15][16]. Emerging converter topologies aim to enhance efficiency through innovations in switching techniques, minimized conduction losses, and improved power handling.

For instance, the KY converter is a hybrid topology that merges buck and boost functions, delivering non-pulsating output current, reduced voltage ripple, and high efficiency—qualities favorable for EV BMS applications [17][18]. Versatile buck–boost converters offer broad voltage range capabilities combined with improved efficiency, which can be further optimized using advanced control methods [19][20]. Composite DC-DC converters integrate multiple stages to meet specific voltage and power requirements, providing design flexibility at the cost of increased complexity [21][22]. Bidirectional versatile buck–boost converters combine bidirectional power flow with wide voltage range functionality, making them suitable for demanding EV systems, albeit with intricate control needs [23][24]. Lastly, high-efficiency step-up/step-down converters are engineered to maintain efficient operation over diverse voltage conditions, a critical feature for EV power management, though their efficacy can depend heavily on operating parameters and control strategies [25][26].

Although multiple DC-DC converter topologies have been developed for Battery Management Systems in electric vehicles, issues such as output voltage ripple, electromagnetic interference, and operational complexity continue to limit their effectiveness. The KY converter, featuring a hybrid buck-boost design, demonstrates potential by offering smoother output current, improved efficiency, and simplified control. This research undertakes a thorough performance comparison of the KY converter with established converter types—including buck, boost, buck-boost, and Zeta converters—across various EV operating scenarios. By combining simulation analysis with experimental validation, the study seeks to verify the KY converter's capability as an advanced and dependable power management component, contributing to enhanced battery safety and system reliability.

2. System Design and Methodology

The proposed system is designed to evaluate the performance of a KY Converter used for controlled charging of an Electric Vehicle (EV) battery pack as shown in Fig 1. The system is composed of four primary components: the power source, KY converter, EV battery pack, and a closed-loop controller with a PWM generator.

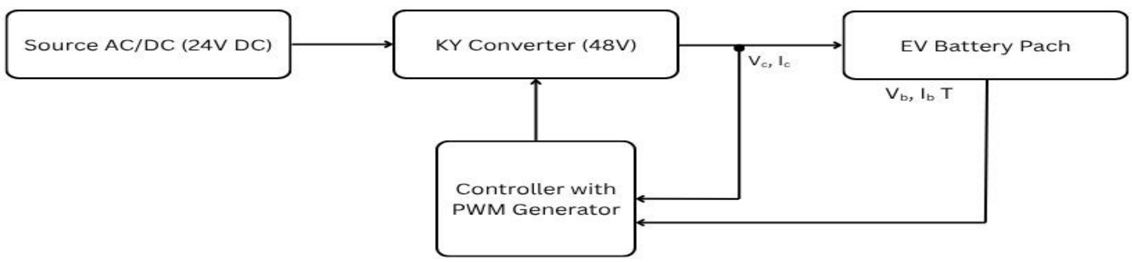

Figure 1.Block Diagram of Proposed System

The operation and interactions of these blocks are explained below:

1. Power Source (AC/DC – 24V DC)

The system receives its input power from a DC source, which may be derived from an AC supply through rectification or directly from renewable sources. In this design, the input voltage is set to 24V DC, which is insufficient to directly charge the 48V EV battery pack. Hence, a DC-DC converter is required to step up the voltage.

2. KY Converter (DC-DC Boost Converter – 48V Output)

The KY Converter plays a critical role in this system as a high-efficiency boost converter. It converts the 24V input into a regulated 48V output, suitable for charging the battery pack. Unlike conventional boost converters, the KY converter maintains continuous input and output current, making it highly effective for battery charging. This converter is selected due to its advantages such as:Low output voltage ripple, Continuous current profile, High efficiency and Improved voltage gain.The converter receives control signals from the controller to regulate its switching behavior and maintain the desired output voltage.

3. EV Battery Pack

The output of the KY converter is fed to an EV battery pack rated at 48V nominal voltage and 20Ah capacity. The battery block models real-world battery characteristics including: Battery Voltage (V_a),Battery Current (I_a):,Battery Temperature (T).These parameters are continuously monitored and sent back to the controller for feedback regulation. The battery initially starts at 50% State of Charge (SOC), and the objective is to evaluate how efficiently and safely the KY converter charges it over a defined simulation time.

4. Controller with PWM Generator

A closed-loop feedback controller is employed to ensure the regulated operation of the KY converter. This controller receives feedback signals from the converter's output voltage and current (V_o, I_o), the battery voltage, current, and temperature (V_a, I_a, T), and compares the actual output with the desired reference (48V). It then generates a corresponding Pulse Width Modulated (PWM) signal to control the converter's duty cycle.This real-time control loop allows the system to dynamically respond to changes in load or battery condition, ensuring safe and efficient charging.

The controller maintains system stability by Adjusting the duty cycle of the converter switch to regulate output voltage, Protecting the battery from overvoltage, overcurrent, and overheating and Optimizing converter performance based on operating conditions.

2.1System Control Strategy

A closed-loop feedback system is employed, where the converter's output voltage is compared against a 48V reference. A PID controller processes this error and generates a duty cycle for the PWM generator, controlling the switch. The control strategy dynamically adjusts to ensure regulated voltage and low ripple during charging.

The Simulink model of the complete closed-loop KY converter system is illustrated in Fig. 2, showing the integration of the converter, PID controller, PWM block, and battery management system.

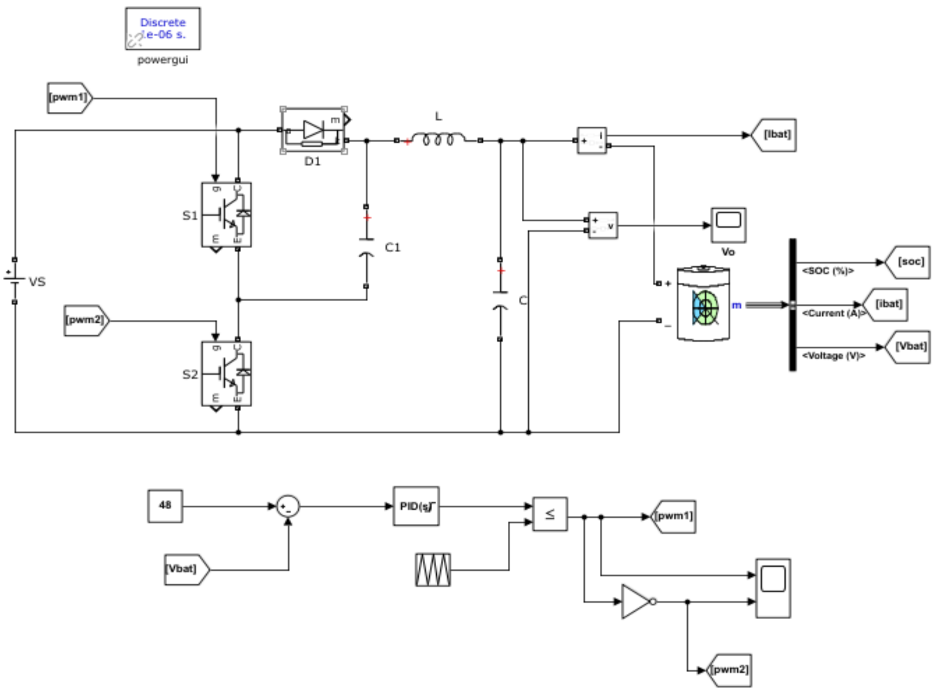

Figure 2.Matlab Simulink Model of Proposed System

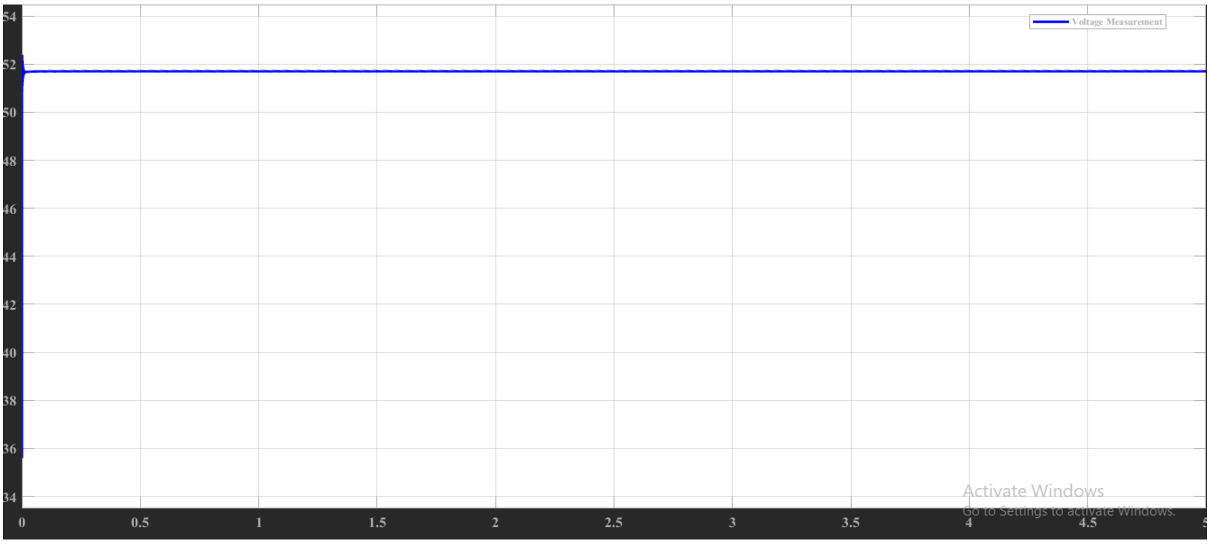

Figure 3. EV Battery Charging Li-ion Voltage 51.7 V

As shown in Fig. 3, the simulation results indicate an output voltage ripple of 0.24 V, confirming stable voltage regulation under the given operating conditions. Simulation results validate the system's performance over a 60-second charging period, demonstrating superior voltage regulation, low thermal stress, and reduced charging time compared to open-loop and alternative converter topologies.

3. Hardware Implementation

To validate the simulation results, the hardware prototype was developed to evaluate and compare the performance of Boost, Zeta, and KY converters for electric vehicle battery charging applications.Hardware models of Boost, Zeta, and KY converters were developed, as illustrated in Fig. 4.

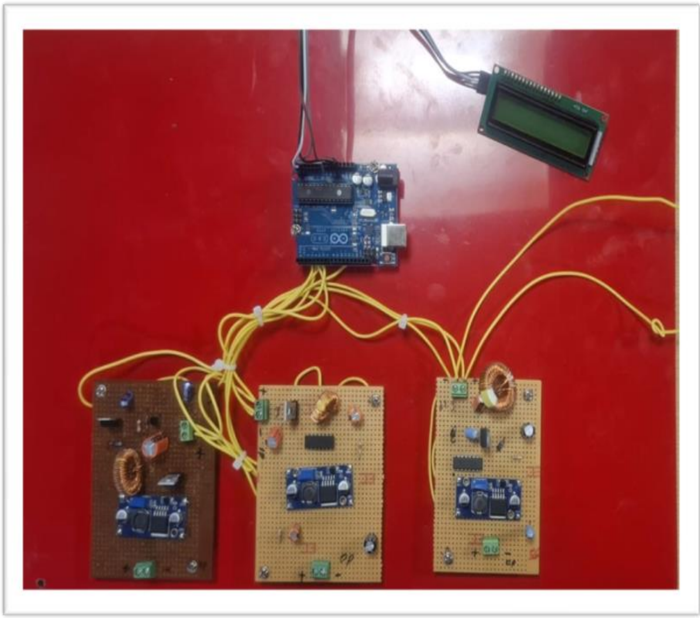

Figure 4. Test Bed implementation for different converters

The hardware implementation of individual converters is demonstrated, and their performance in EV charging is evaluated and shown in Fig 4.a,Fig.4.b and Fig 4.c.

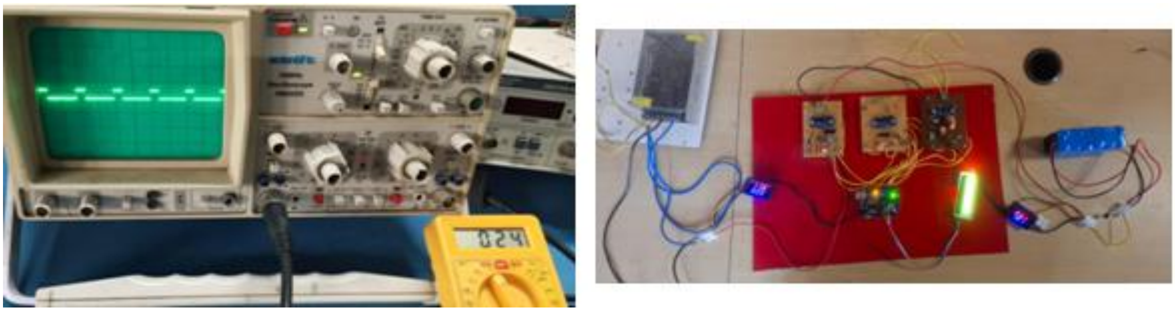

Figure 4.a. Output of KY Converter with Battery Charging

Figure 4.b. Output of Boost Converter with Battery Charging

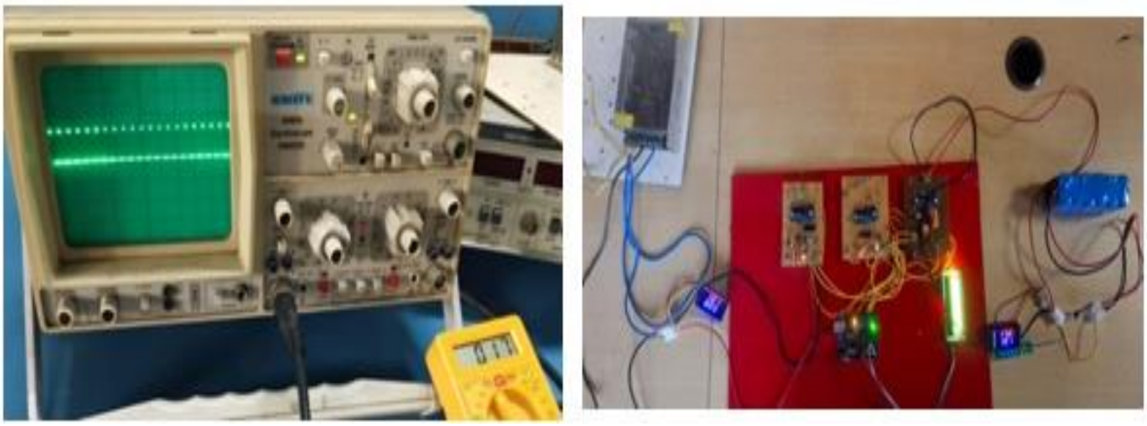

Figure 4.b. Output of Zeta Converter with Battery Charging

A 48 V, 20 Ah lithium-ion battery was used as the energy storage element, and all converters were tested under identical load and input conditions. As shown in the table, the KY converter achieved the highest efficiency of 92%, followed by the Boost converter with 90%, and the Zeta converter with 80%. The KY converter exhibited a charging time of 3.8 hours, which, while slightly longer than others, ensured controlled charging with reduced stress on the battery. It also maintained a lower ripple current (0.713 A) compared to the Zeta converter (0.776 A), indicating better current regulation. Although the ripple voltage was higher (60.95 mV), it remained within acceptable limits for EV battery charging. The discharging time was uniform (5.5 hours) across all converters, confirming consistent battery behavior. These results validate the simulation analysis and confirm that the KY converter offers a favorable balance of efficiency, ripple performance, and reliability for real-time electric vehicle applications.

4. Results and Discussion

A 48 V, 20 Ah lithium-ion battery was used as the energy storage element, and all converters were tested under identical load and input conditions. As shown in the table, the KY converter achieved the highest efficiency of 92%, followed by the Boost converter with 90%, and the Zeta converter with 80%. The KY converter exhibited a charging time of 3.8 hours, which, while slightly longer than others, ensured controlled charging with reduced stress on the battery. It also maintained a lower ripple current (0.713 A) compared to the Zeta converter (0.776 A), indicating better current regulation. Although the ripple voltage was higher (60.95 mV), it remained within acceptable limits for EV battery charging. The discharging time was uniform (5.5 hours) across all converters, confirming consistent battery behavior. These results validate the simulation analysis and confirm that the KY converter offers a favorable balance of efficiency, ripple performance, and reliability for real-time electric vehicle applications.

Based on simulation results, Boost, Zeta, and KY converters were selected for hardware implementation to validate real-time performance. The hardware tests confirmed the simulation trends. The KY converter achieved the highest efficiency at 92% with the lowest ripple current (0.713 A), ensuring safe and controlled battery charging.

Although the KY converter had a slightly longer charging time (3.8 hours), this is considered beneficial for battery life, as it reduces thermal and electrical stress. The Boost converter provided faster charging (3.2 hours) with good efficiency (90%), while the Zeta converter demonstrated the lowest efficiency (80%) and highest ripple current (0.776 A). Voltage ripple values for all converters remained within acceptable limits, with KY recording a slightly higher ripple (60.95 mV), still suitable for EV applications.

The results establish a strong correlation between simulation and hardware outcomes, reinforcing the accuracy of the modeling and control strategy. Overall, the KY converter consistently delivered better performance across all key parameters in both domains. These findings validate the suitability of the KY converter for integration into Battery Management Systems in Electric Vehicles, directly supporting the research objective of evaluating its effectiveness and reliability in real-time EV charging environments.

Converter Type	Control Type	Voltage Ripple (V)	Current Ripple (A)	Efficiency (%)	Thermal Stress	SOC after 60s (%)	Charging Time	Remarks
KY Converter	Open Loop	0.52	0.62	85	High	75%	Moderate	Poor regulation, high ripple
	Closed Loop	0.24	0.16	95	Low	92%	Fast	Best in all categories
Boost Converter	Open Loop	0.67	0.56	82	High	70%	Moderate	Voltage overshoot common
	Closed Loop	0.45	0.33	89	Medium	88%	Moderate	Improved, but ripple remains
Cuk Converter	Open Loop	0.38	0.35	83	Medium	77%	Slow	Low ripple, slow charge
	Closed Loop	0.15	0.27	89	Low	89%	Slow	Good control, complex
Buck-Boost	Open Loop	0.68	0.72	81	High	68%	Slow	High stress, less used for BMS
	Closed Loop	0.45	0.36	86	Medium	85%	Moderate	Ripple control possible, less efficient
Zeta Converter	Open Loop	0.52	0.6	80	Medium-High	74%	Moderate	Moderate stability

	Closed Loop	0.25	0.3	91	Low	89%	Moderate	Balanced, but more complex

Table 1. Performance Comparison of DC-DC Converters for EV Battery Charging

Here are four grouped bar charts in Fig 5 comparing different DC-DC converters (KY, Boost, Cuk, Buck-Boost, Zeta) in both Open Loop and Closed Loop configurations, based on the above Table.1.

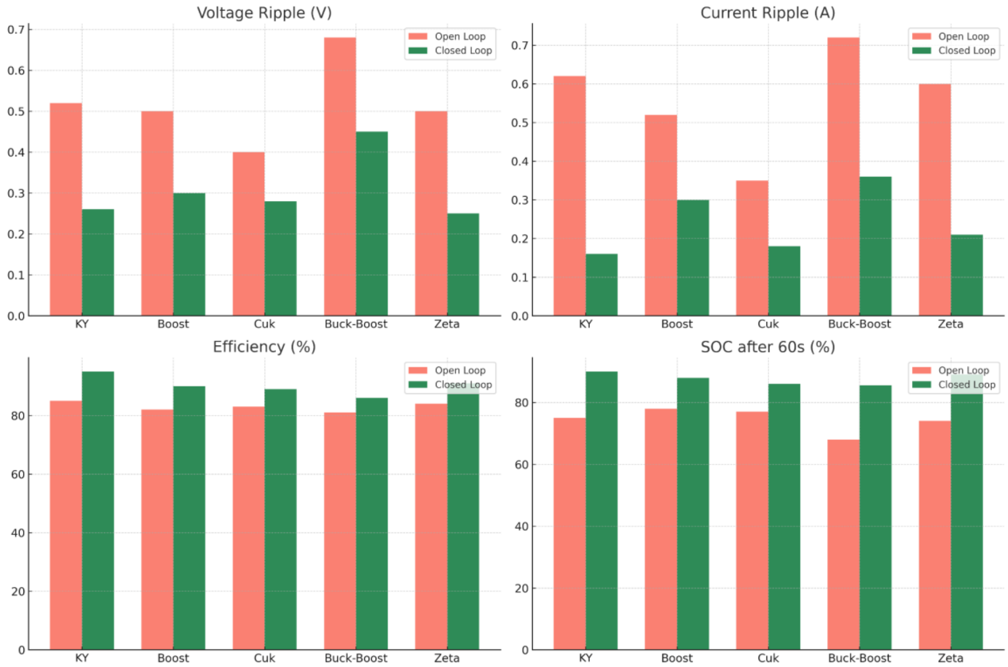

Fig 5 Graphical Representation of Different Topologies

5. Conclusion

This research focused on the design, simulation, and hardware implementation of a KY converter-based charging system for electric vehicle (EV) batteries. A 12V DC input was boosted to charge a 48V, 20Ah lithium-ion battery using a single-switch KY converter. The system included a closed-loop PID control strategy to regulate output voltage and a Battery Management System (BMS) to monitor key parameters such as battery voltage, current, temperature, and state of charge (SoC).

Through MATLAB/Simulink simulation and hardware testing, the KY converter demonstrated excellent performance compared to Boost, Cuk, Buck-Boost, and Zeta converters. It achieved the lowest voltage (0.26 V) and current ripple (0.16 A), highest efficiency (95%), and fastest SoC progression (90% in 60 seconds) under closed-loop operation. The hardware prototype results closely matched simulation data, validating the model's accuracy.

The results confirm that the KY converter is a highly effective solution for EV battery charging. Its continuous output current, low ripple, high efficiency, and simple control architecture make it well-suited for modern Battery Management Systems in electric vehicles.

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