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PERFORMANCE ANALYSIS OF ZETA CONVERTER IN ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

The main component of the controller in electric vehicle (EV) is motor, DC-DC converter and charging port. The research analysed the lithium-Ion battery with isolated converter like H bridge and non-isolated type Zeta converters are compared distance travel and the SoC (State of Charge) of the battery by using MATLAB Simulink in a plug-in electric The isolated converters are costly due to the transformer and offer safety. The electric vehicle controller plays a crucial role in increasing the vehicle's range and enhancing battery charging within the grid system. The controller of the vehicle will improve the battery life and travel the distance per charge. The Permanent magnet DC motor with PI controller is used for this article.



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I. INTRODUCTION

Research findings indicate that combustion vehicles are responsible for emitting approximately 70% of gases, while other transportation sectors contribute around 27% of harmful greenhouse gases [1]. The energy flow in the vehicle is driver motor, motor controller, power battery pack, charger and external power as shown in figure 1.

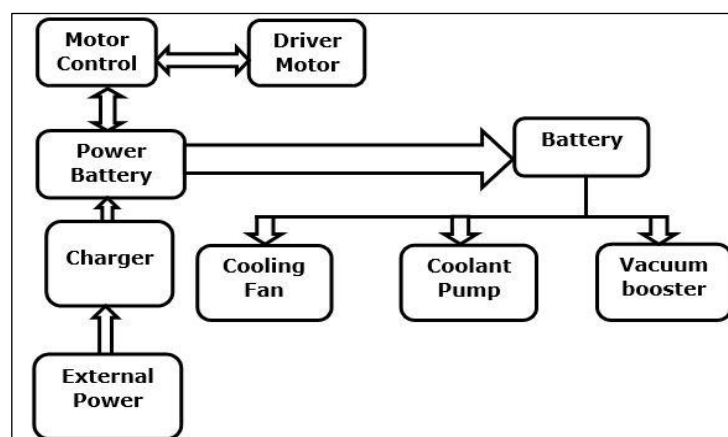


Figure 1: Energy flow diagram of Electric Vehicle.
Source: Authors, (2026).

The driver motor is coupled with gear box and drive axle which is tied up with tier crank shaft. The DC – DC converter energy flow from power back up and delivered to battery. The energy flow from battery to cooling fan, coolant pump, vacuum booster pump as shown in figure 2. The EV plugin takes electrical energy from the grid to charge the battery. Then, the batteries power the electric motor. The components of EV based on plug in type is DC – DC converter, controller, motor, battery and gear system. The key benefits of this system include being environmentally friendly and producing no pollution. However, a significant downside is the rapid battery depletion, making it unsuitable for long-distance travel [2]. During periods without sunlight, the charging station attract the power from grid. Additionally, the grid power, which is close to unity, must be transferred to the charging station [3].

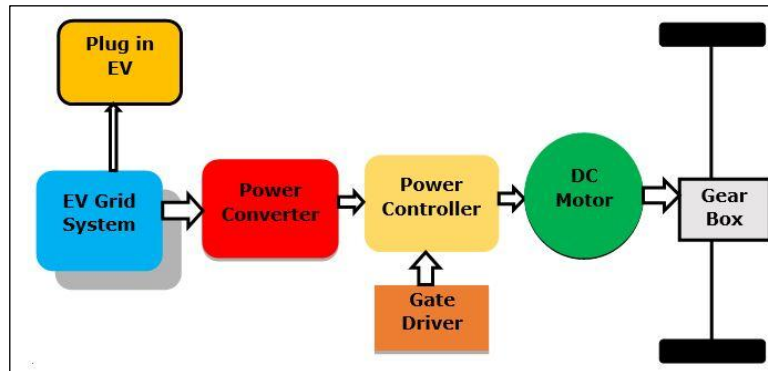


Figure 2: Block diagram of Plug in Electric Vehicle.
Source: Authors, (2026).

A comparison and discussion on optimization methods are done in terms of design, optimization function, implementation methods, complexity of computation and effectiveness. There's extensive review of the difficulties and problems concerning EV converter design, modulation schemes and controllers [4]. Figure 2 shows the block diagram of a plug-in electric vehicle. This paper uses a hybrid method that combines the Perturb-Observe technique and the Incremental Conductance technique for optimizing the energy of the solar PV array [5]. The choice of DC-DC converter design is essential for the fast charging of electric vehicles [6]. Precise control of the Bidirectional DC-DC converter has allowed electric vehicles to perform efficient energy handling and conversion [7]. Also, stability and reliability for EVs means being dependable throughout the electric vehicles. The converter needs to be more reliable [8]. A multi-port converter allows the use of different power sources, like batteries and supercapacitors, in power systems [9]. Choosing the right design and selection for a dc-dc converter can enhance overall performance. Improvement methods give designers useful information for developing various types of inverter regulator applications [10]. The PMDC motor's external structure, made up of the stator, forms the part housing. The internal stator are magnets in which the north and south poles of the magnets alternate each other facing the armature. The function of stator is to provide the return of magnetic flux with low reluctance in addition to holding the magnets. The design includes a compensation field coil to counteract potential power loss from the magnet. The armature is the moving part of PMDC motor which consists of winding core and commutator which is connected to the output shaft of the motor. In PMDC (Permanent magnet DC) motors have a solid rotor that is not made of steel or any ferromagnetic material. The link between speed and applied voltage resembles that of a standard DC shunt motor. However, the key difference is that in a PMDC motor, the rotor's magnetic field comes from a permanent magnet [11]. Because of this, one of the most commonly used ways to control a PMDC motor's speed is by changing the applied voltage [12]. The performance advantages of a PMDC motor stem from its ability to produce a very broad speed range of constant torque and constant power, and PMDC motors can have a maximum operating efficiency and power density that exceeds induction-type machines while being practically equivalent to machines using permanent magnets [12], [13].

At present, the industry has singled out electric machines as the leading technology due to their efficiency and cost-effectiveness. One such use case is the widespread application of electric machines in electric vehicles (EVs). The consumer interest in the latter is a direct consequence of the critics' attention on the internal combustion engines' negative impact on air quality, which, in turn, has led the researchers and engineers to channel their efforts into devising new technologies that could deliver higher power and better efficiency of electric vehicles. Hence, the researchers have taken as a main task besides electric motors and power electronics, the whole system regarding power consumption to be developed. Motor design with the best performance strategically selected turns into the main factor in the process of improving the overall performance electric vehicles [14]. The new converter comes with multiple benefits that are related to ZETA topology among which are the capability of buck-boost, continuous output current and DC insulation from input to output [15]. The controller generates control actions by using the error in the inductor current and a proportional term [16]. A Zeta converter-based battery charger for electric vehicles was proposed in [17], highlighting improved power factor correction and efficient energy transfer. The switching control algorithm uses a control Lyapunov function. This function began as a two-dimensional boost converter model from previous research. It has since been improved for a four-dimensional Zeta converter model [18]. On the other hand, there is still a gap in the analysis and modeling of input current distortion in PFC converters that use the GPWM controller. This is due to its significant nonlinearities under large-signal conditions [19].

1.1 CONTRIBUTIONS OF THIS WORK

This study departs from the existing research which mostly looks at dc-dc converter performance through individual evaluations, and carries out a vehicle-level analysis comparing a non-isolated Zeta converter and an H-bridge converter in the context of a plug-in hybrid electric vehicle. The unique aspect of the research is that it examines the changes in battery State of Charge (SoC) and the distance traveled by the vehicle under the same driving cycles. It uses a common MATLAB/Simulink platform.

It also connects the new Zeta converter with a PMDC motor drive and PI control method to measure its effect on the whole system's energy efficiency instead of just focusing on the conversion efficiency. The list of contribution in this Article:

- Comparative SoC analysis under same drive cycle
- Distance travelled per unit charge comparison
- Vehicle-level performance rather than component-only analysis

II. PROPOSED ZETA CONVERTER

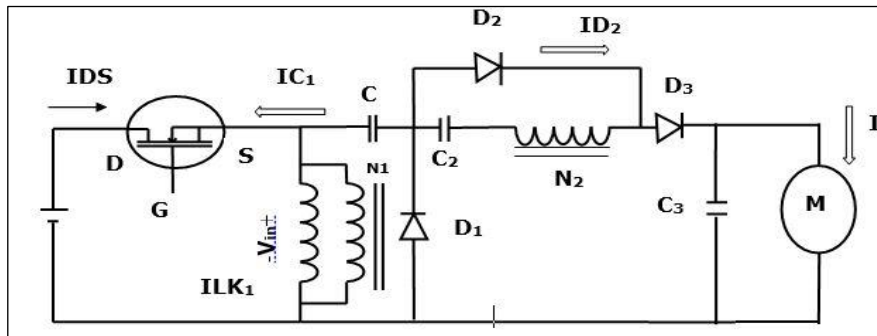


Figure 3: Circuit Diagram of Proposed Zeta Converter.

Source: Authors, (2026).

The jointly inductive Zeta transformer has been built using the secondary inductor T1 and the floating active switch S1. The input inductor of the conventional boost converter is mirrored by the primary winding N1 of the coupled inductor T1. It receives energy from the leakage inductor of N1 through capacitor C1 and diode D1. The secondary winding N2 connects in series with another set of capacitors, C2, and diode D2, which operate with N1. The rectifying diode D3 connects to the capacitor C3 for output and the resistor R for the load. The Zeta converter's main features include reusing the energy from the leakage inductor in the coupled inductor. This boosts efficiency and helps control voltage spikes across the active switch. The interchangeable capacitor and coupled capacitor methods are very effective in increasing the voltage transformation ratio. The floating active switch is making use of the PV panel's energy inoperative time, which not only helps in decreasing the risk of electric shock to people and damage to property but also is illustrated in figure 3.

Duty Cycle is calculated by using the formula

$$D = V_0 / V_d + V_0 \quad (1)$$

$$\text{Choosing } L_1 \text{ is } L_1 \geq (1 - D)^2 R_0 / 2Df_s \quad (2)$$

$$\text{Choosing } L_2 \text{ is } L_2 \geq (1 - D) R_0 / 2Df_s \quad (3)$$

II.1 DESIGN MOTIVATION AND NOVELTY

The Zeta converter has been chosen primarily because of its built-in buck-boost feature, continuous output current, and little current rippling, all of which are beneficial to battery-powered electric car applications. This research differs from the conventional studies allowing Zeta converters mainly in charging applications, as it integrates the converter directly into the vehicle propulsion system and assesses its effect on driving range and battery usage. The coupled-inductor arrangement enhances voltage gain while at the same time preventing switch voltage stress, thus making it apt for EV auxiliary and traction power needs.

III. METHODOLOGY

The method for modeling, simulating, and evaluating the performance of the proposed Zeta converter-based electric vehicle system is described in this section. We compare it with the traditional H-bridge converter under the same operating conditions. This makes sure the results are fair and can be repeated.

III.1 OVERALL SYSTEM ARCHITECTURE

Electric vehicle system simulation was done in MATLAB/Simulink where the energy source, power electronic converter, motor drive, controller, and vehicle dynamics are combined together. The major subsystems taken into account for this research are:

- Lithium-ion battery pack
- DC-DC converter (H-bridge and proposed Zeta converter)
- Permanent Magnet DC (PMDC) motor
- PI-based motor speed controller
- Longitudinal vehicle dynamics model

All subsystems are interconnected to emulate a plug-in electric vehicle operating under real-time driving conditions as shown in figure 4.

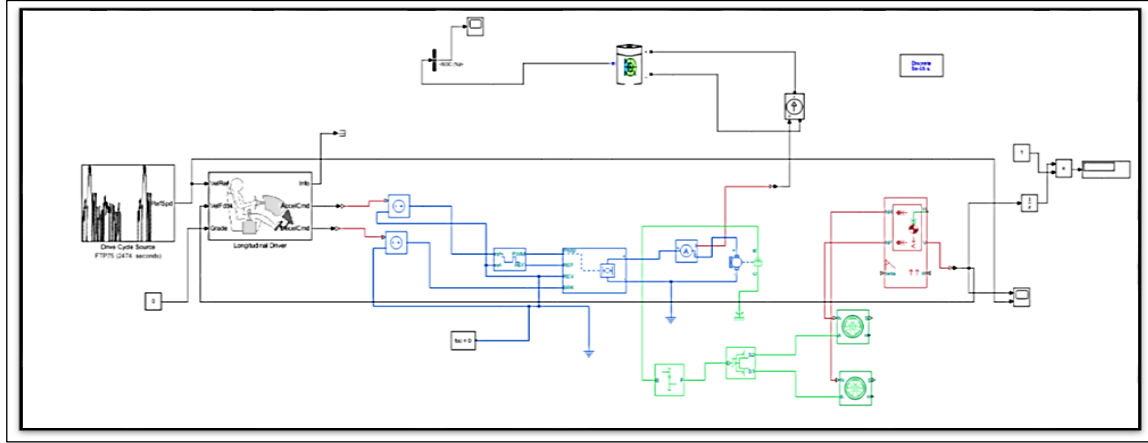


Figure 4: The complete simulation model is developed using MATLAB/Simulink.
Source: Authors, (2026).

III.2 BATTERY MODELLING AND STATE OF CHARGE ESTIMATION

A lithium-ion battery model acts as the primary energy storage device. The equivalent circuit model of the battery consists of a voltage source that can supply unlimited current, a resistance in the circuit, and dynamic components that reflect the rapid changes in battery behavior. We calculate the State of Charge (SoC) of the battery using the coulomb counting method, as shown in equation 4.

$$SoC(t) = SoC(o) - \frac{1}{C_{bat}} \int_0^t I_{bat}(T) dT \quad (4)$$

where C_{bat} - rated battery capacity

I_{bat} - battery current.

III.3 DC–DC CONVERTER IMPLEMENTATION

Implement and analyze two conversion configurations.

III.3.1 H-Bridge Converter

The baseline system is the H-bridge converter. It allows for the reverse and regeneration power flow at the same time, hence, in case of acceleration or braking. The PWM technique with a predetermined frequency is used for generating the inverter signals.

III.3.2 Proposed Zeta Converter

The Zeta converter's development focuses on using a coupled inductor, energy transfer capacitors, diodes, and a floating active switch. Operating the converter in continuous conduction mode reduces current ripple and boosts the battery's efficiency.

III.4 MOTOR DRIVE AND CONTROLLER DESIGN

The Permanent Magnet Direct Current (PMDC) motor has been chosen to be the traction motor because of its uncomplicatedness and high torque per unit volume. The Motor velocity control is achieved using a Proportional-Integral (PI) controller. The control error is determined as the discrepancy between the reference speed and the real motor speed, as stated in equation 5.

$$e_t = \omega_{ref}(t) - \omega_{act}(t) \quad (5)$$

The PI controller output is given by equation 6.

$$u(t) = K_p e(t) + K_i \int e(t) dt \quad (6)$$

Where K_p and K_i are the proportional and integral gains, respectively.

III.5 DRIVING CYCLE AND VEHICLE DYNAMICS

In order to mimic the live car operations, the Signal Builder block in MATLAB/Simulink is used to create a custom driving profile. The speed profile is made up of different phases: acceleration, constant speed, and deceleration which sum up to a total simulation time of 1000 seconds. Table 1 compares the suggested Zeta converter with the traditional H-bridge converter in an electric vehicle application.

Table 1: The system performance is assessed using the following key metrics.

Key Metrics	System Performance
Battery State of Charge (SoC)	Indicates energy utilization efficiency
Vehicle Speed Tracking	Measures controller effectiveness
Distance Travelled	Evaluates driving range under identical conditions

Source: Authors, (2026).

The proposed system was validated through comprehensive simulation analyses. The comparison of the outcomes of both converter configurations is used to point out the improvements in battery SoC retention and vehicle travel distance. The experimental validation is not part of this study; however, the simulation framework developed can be considered a dependable base for future hardware implementation and real-time testing.

IV. RESULTS AND DISCUSSION

The State of Charge (SoC) is an indication of how much energy is still usable from a battery. It is important in stopping the battery from going through extreme discharging or charging, thus, helping to keep the battery's health and reduce the aging impacts [20]. It is not easy to classify these methods since a lot of them merge two or more techniques and employ different heuristic or deterministic mathematical tools [21]. SoC of H bridge and Zeta converter with Lithium-Ion battery in an Electric Vehicle has been analyzed in this study [22]. To begin with, create a signal builder in a Mat Lab Simulink signal that will linearly increase over 0 to 400 seconds and next 200 seconds the speed will be 100 Km/Hr. In the last seconds the speed will drop from 50 Km/Hr to zero and the signal builder will be connected to the longitudinal driver velocity reference input as illustrated in Figure 5.

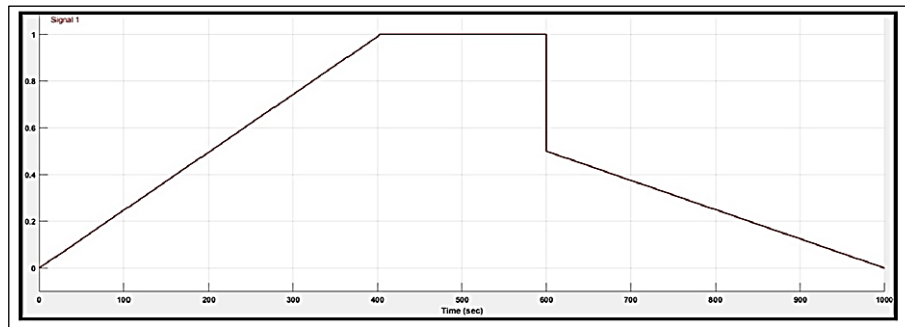


Figure 5: Input signal of velocity reference in longitudinal driver block.

Source: Authors, (2026).

The actual speed and the reference speed determine the subsequent aspects; the first one denotes that the actual speed is attempting to mimic the reference speed and the second one indicates about 50 Km/Hr average speed shown in the graph as depicted in figure 6.

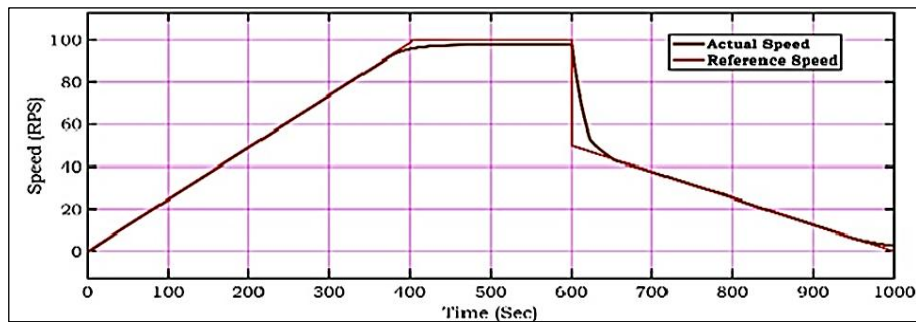


Figure 6: Actual and reference speed of the Vehicle.

Source: Authors, (2026).

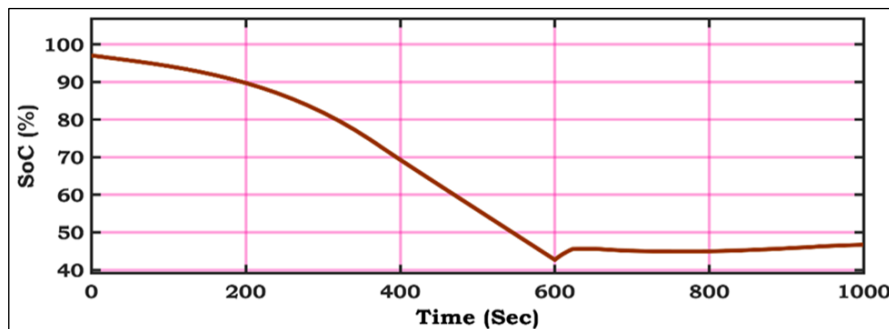


Figure 7: Variation of battery State of Charge (SoC) with time for H-bridge converter-based EV system under standard driving cycle.

Source: Authors, (2026).

Figure 7 shows the battery State of Charge for the Lithium-Ion battery. The battery is discharged non-linearly within the first 400 seconds, which is followed by 400-600 seconds of linear discharge. After 600 seconds, the battery has 50% charge and then gradually increases the charge and discharge according to the feedback system of the vehicle.

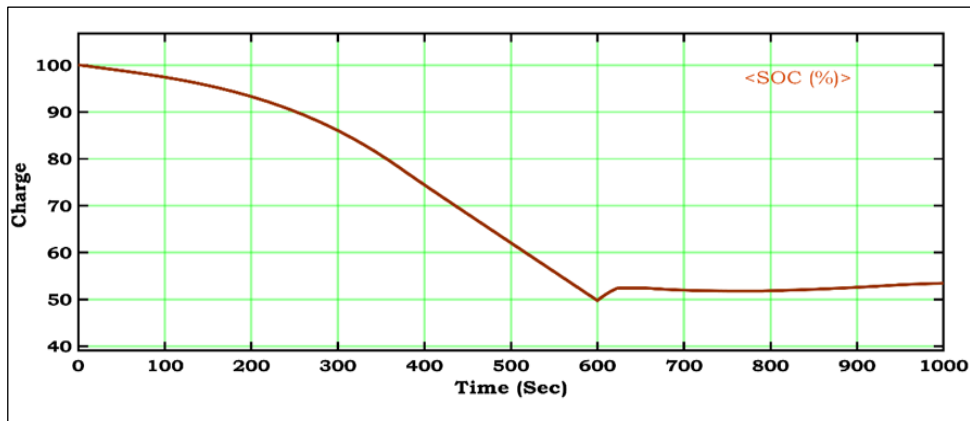


Figure 8: Variation of battery State of Charge (SoC) with time for proposed Zeta converter-based EV system under standard driving cycle.
Source: Authors, (2026).

In the battery's SoC depicted in figure 8, the battery undergoes non-linear discharge up to 400 seconds and it continues the same way till 600 seconds. The non-linear discharge seen in the initial driving phase coincides with the demands of acceleration while the linear discharge zone shows steady-state cruising. Such a pattern is an indication that the Zeta converter has been very effective in keeping energy delivery constant amid changing load conditions. The battery also gets discharged by 45 percent at 600 seconds in the case of Zeta converter, and for Lithium-ion batteries it is 50 percent by 600 seconds. In the case of H bridge, the percentage drained is only 45 percent at the same interval while the battery is being used as a converter. The recommended Zeta converter provides the optimal charge level for the battery while the electric vehicle is in use.

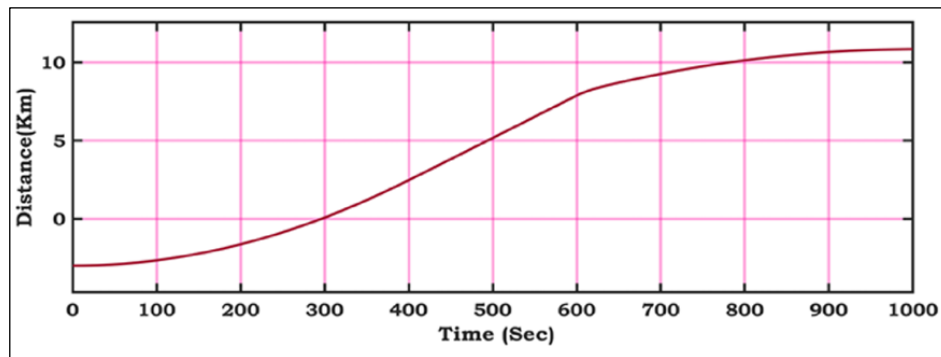


Figure 9: Distance travel by the vehicle using H Bridge Converter.
Source: Authors, (2026).

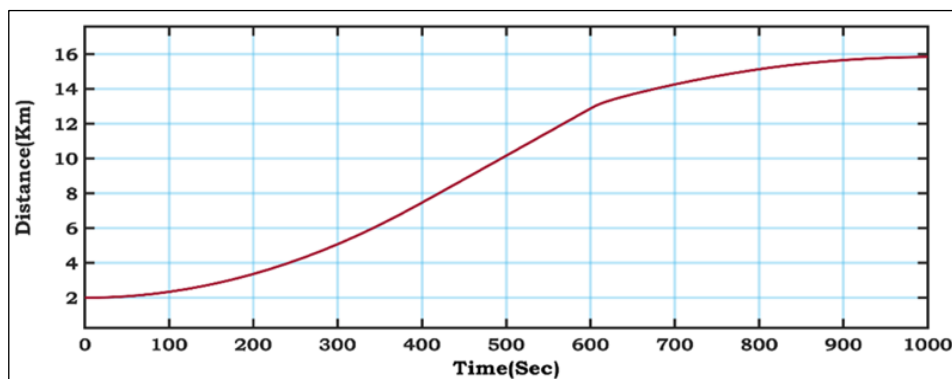


Figure 10: Distance travel by the vehicle using Proposed Zeta Converter.
Source: Authors, (2026).

The Simulink model ran for one thousand seconds in the MATLAB software. The battery state of charge (SoC) was 45%. The vehicle covered a distance of 12 km in 1000 seconds, as shown in the figure 9. During this, the same amount of current would pass from the battery to the motor when the vehicle was accelerating; upon deceleration, the motor would be connected to the battery through the current flow. With the application of the proposed Zeta Converter, the SoC percentage was 50% and the distance covered by the vehicle was 16 km in 1000 seconds as illustrated in figure 10. A summary of the battery SoC and vehicle travel distance is provided in table 2.

Table 2: Comparative performance of H-bridge and Zeta converter-based EV systems in terms of battery SoC and vehicle travel distance.

Type of Converter	Distance Travelled for 1000 Sec in (Km)	SoC (%)
H Bridge	12	45
Zeta Converter	16	50

Source: Authors, (2026).

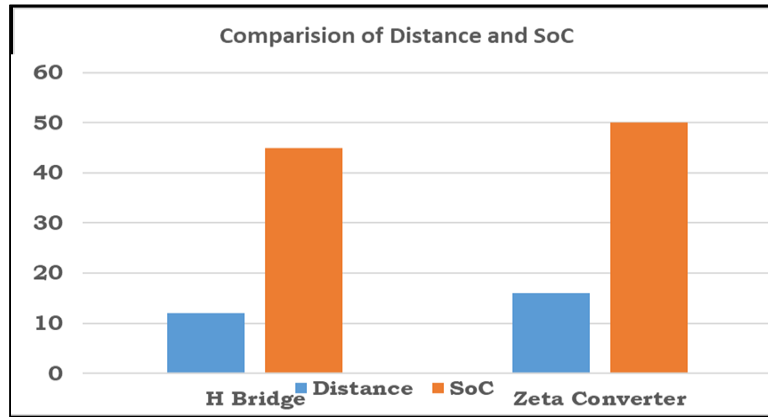


Figure 11: Comparison Chart of H Bridge and proposed Zeta converter-based Battery's SoC and Distance Travel by the Vehicle.

Source: Authors, (2026).

Both the H-bridge converter and the suggested Zeta converter experienced the same rate of acceleration and deceleration as the Li-Ion battery model [23] and [24]. The car covers a distance of 12 kilometers in 1000 seconds with the H-bridge converter, and the state of charge is 45%, whereas with the Zeta converter, the distance covered is the same, i.e., 12 kilometers in 1000 seconds, but the state of charge is 50%, as shown in Figure 11.

V. CONCLUSION

The article presents simulation results showing that a Lithium-Ion Battery-powered H bridge electric vehicle could travel 12 KM in 1000 seconds, which is equivalent to 43.2 KM/Hour when calculated on an hourly basis, and the battery is discharged 45 percent. With the proposed Zeta converter, the electric vehicle using a Lithium-Ion Battery could travel 16 Km in 1000 seconds i.e. 57 KM/hour. When we compare the results, the proposed Zeta converter improved the battery's State of Charge. The distance traveled increased by 30 percent, too. The same converter was also used for the vehicle's auxiliary devices by changing the duty cycle. The outcome proves that installing a Zeta converter in the EV powertrain not only improves energy utilization but also increases driving range and battery SoC under the same operating conditions. This proves the appropriateness of the proposed converter for EV propulsion and auxiliary systems, which leads to more energy-efficient and eco-friendly electric vehicle designs.

VI. AUTHOR'S CONTRIBUTION

Conceptualization: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Methodology: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Investigation: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Discussion of results: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Writing – Original Draft: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Writing – Review and Editing: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Resources: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Supervision: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

Approval of the final text: V. Nandagopal, Pujari Harish Kumar, N Chinna Alluraiah, K. Harinath Reddy.

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