

Development of Bi-Directional Boost-Zeta Converter for Battery Storage Based Grid Tied EV Traction System

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ABSTRACT: Electric vehicles (EVs) rely heavily on efficient power conversion systems to manage energy between the battery and the motor. Therefore, this paper proposes an evaluation of a high-gain bidirectional DC-DC converter integrated with a DC drive system, featuring regenerative braking capability for EV applications. Proposed System includes a high-gain bidirectional converter based on a Zeta-Boost topology, enabling effective power flow between the battery, DC drive, and grid. During motoring mode, energy from the battery is directed to the load (DC drive) through the converter, ensuring sufficient propulsion power. In regenerative braking mode, the kinetic energy of the vehicle is recovered and converted back to electrical energy, which is then stored in the battery, enhancing overall system efficiency. A single-phase voltage source inverter (VSI), driven by DSP-based PWM signals and isolated via driver circuits, enables bidirectional power transfer to and from grid. Controllers maintain constant DC link voltage, regulating drive current, and managing power balance. The LC filter at the inverter output ensures smooth grid interfacing by reducing harmonics. This integrated system not only improves energy recovery during braking but also provides stable operation under varying load conditions, contributing to enhanced energy management and drive performance. This novel approach is implemented by using MATLAB/Simulink and attains enhanced converter efficiency of 98.28% and voltage gain of 15.4%, respectively.

Keywords: Electric vehicles, high-gain bidirectional Zeta-Boost converter, single-phase voltage source inverter, PI controller, MATLAB/Simulink.

1. Introduction

The air quality in major cities has deteriorated to unhealthy levels, creating an urgent need to reduce greenhouse gas emissions and implement clean mobility solutions. To address this, the government has committed to a significant shift toward EVs. The support for this transition by offering incentives for EV purchases and issuing researchers to establish a robust charging infrastructure nationwide [1-3]. However, there

are various key challenges faced in ensuring the widespread adoption and success of EVs. The expansion of charging infrastructure is still incomplete. Efforts are underway to integrate renewable-powered charging points into existing fuel stations [4]. Yet, one major challenge is the high cost of renewable energy needed for fast charging. Additionally, the development and analysis of reliable and efficient power converter topologies remain in the research and development phase [5]. Considering these factors,

this article examines a DC drive system, featuring regenerative braking capability. EVs are classified based on their energy sources, traction systems, and available charging facilities. The power distribution system in an EV comprises several power electronic converters at various stages, including battery charger, traction inverter, and high-voltage to low-voltage DC-DC converter [6]. EV battery charger converts AC grid voltage into necessary DC voltage to power battery, which then supplies energy to traction inverter. In cases where inverter's voltage requirement exceeds the battery voltage, or when battery voltage variations affect inverter performance, the battery charger must adapt, increasing development complexity [7]. To address these issues, a bi-directional DC-DC converter is placed between the battery and traction inverter, boosting battery voltage to match inverter's needs. Bi-directional DC-DC converters improves drive capabilities and extend battery lifespan. Enhanced battery life is attributed to minimize ripple current and regulate charge and discharge cycles of battery [8]. Various research has been conducted to evaluate the compatibility and effectiveness of different converter topologies within this architecture.

A bidirectional DC-DC Zeta converter, based on the Zeta architecture, is a type of power electronic circuit designed to facilitate bidirectional energy transfer between two DC voltage sources with differing voltage levels. The Zeta topology integrates the principles of Buck and Boost configurations, enabling both voltage step-up and step-down operations using a single inductor. However, it involves conduction losses and affect overall efficiency [9]. Bidirectional buck-boost converter is utilized for regulation of battery and DC link voltages under a wide range of source variations. Nevertheless, it encounters problems such as efficiency losses arise, particularly under

dynamic operating conditions [10]. The proposed converter achieves a high voltage gain through its voltage doubler configuration at the output. Additionally, it utilizes soft-switching and synchronous rectification techniques, enhancing its overall efficiency. The DC output significantly reduces the size of filters while improving electromagnetic interference (EMI) performance. This not only enhances system dynamics and reliability but also offers additional benefits like flexibility in battery specifications (voltage ratings), reduced input filter requirements, and improved battery lifespan. Furthermore, this architecture facilitates the integration of other energy sources, such as ultra-capacitors, alongside the EV battery. The major contributions of the proposed work are:

- Novel bidirectional boost-zeta converter, ensures efficient bidirectional power flow, providing enhanced voltage regulation by stepping up or stepping down voltage between the battery and DC link, while its high voltage gain capability makes it ideal for managing varying voltage levels in energy systems.
- Bidirectional converter interfaces with the battery by managing its charging and discharging while ensuring efficient operation, and employs current control to optimize charging times and prevent overcharging or deep discharging.

2. Proposed Work Explanation

The proposed control system for a grid-connected EV traction system powered by battery storage is depicted in fig.1. Its primary focus is the innovative design of a bi-directional boost-zeta converter. The system incorporates various critical components and control mechanisms to regulate transfer of power between battery, DC link, and grid.

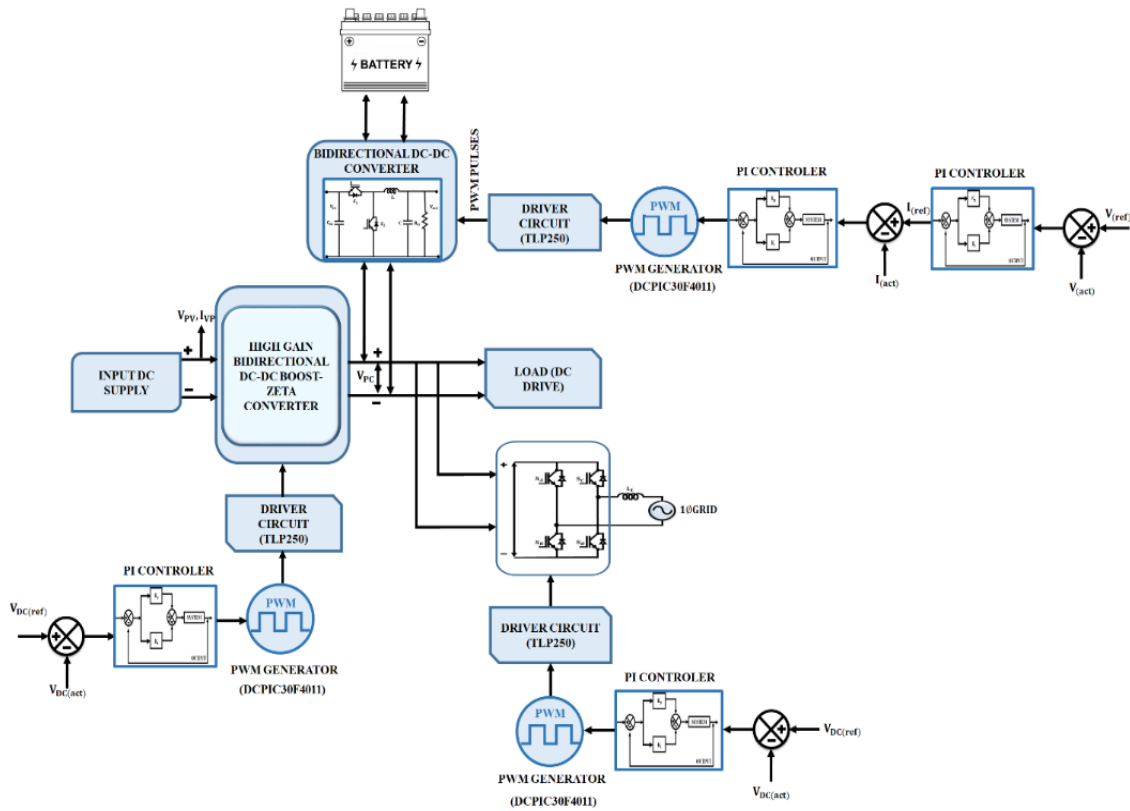


Figure 1: Block diagram of proposed model.

The proposed system gets powered by DC supply and it is fed into a bidirectional DC-DC converter to manage battery charging and discharging operations in the grid-tied EV traction system. A novel bidirectional boost-zeta converter is integrated that provides bidirectional power transfer between battery and the DC link. Energy gets boosted from the battery to DC link, in boost mode and the power is stepped-down, in zeta mode for charging the battery. The bidirectional converter operations are controlled by taking $V_{DC(act)}$ and $V_{DC(ref)}$ as inputs, producing a control signal. The PWM generator produces switching signals based on the control signal of the PI controller. The PWM signals are further amplified by driver circuit for controlling switching operations in the converter. The battery stores or absorbs energy based on the operating mode. The battery charging and discharging conditions are regulated by the bi-directional DC converter, it incorporates voltage sensing, a PI controller, a PWM generator, and a driver circuit to effectively regulate power transfer to and from the battery. The DC power attained from the

bidirectional DC converter, is fed into 1 Φ VSI, to perform DC-AC conversion for grid integration. The LC filter smoothens the AC power and fed into the grid with reduced harmonics. Thus, the proposed system supports bidirectional power flow

3. Proposed System Modelling

3.1 High-Gain Bidirectional Converter Based On a Zeta-Boost Topology

Power electronic converters play a vital role in applications such as renewable energy systems, EV, and battery energy storage systems. Among these, bidirectional DC-DC converters stand out due to their ability to facilitate energy transfer in both directions, thereby improving efficiency and operational flexibility. Proposed Boost-Zeta converter represents a hybrid topology that integrates functionalities of boost and Zeta converters as depicted in fig.2. When adapted for bidirectional operation, it offers seamless input and output current, versatile step-up and step-down voltage capabilities and improved power density and enhanced efficiency.

The Zeta converter utilizes diodes D_1, D_2, D_3 , inductors L_1, L_2, L_3 , capacitor C_Z and switch S_1 . While the Boost converter incorporates diodes D_4, D_5, D_6 , inductors L_4, L_5 , capacitor C_B and switch S_2 . In this configuration, Zeta converter's switch S_1 is connected to positive polarity of input supply, and Boost converter's

switch S_2 is connected to negative polarity of input supply. Diodes D_1, D_2, D_3 and D_4, D_5, D_6 function in a complementary manner with respect to switches. Additionally, inductor L_3 and capacitor C serve as a low-pass LC filter, bridging hybrid bidirectional network and load.

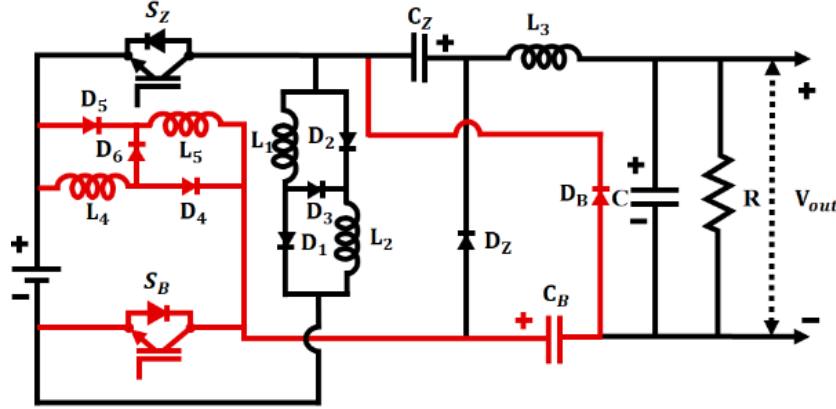


Figure 2: Hybrid zeta-boost converter.

Mode 1: (S_1 and S_2 are ON)

In proposed converter's operation mode, both switches S_1 and S_2 are activated simultaneously. During this phase, input source charges inductors L_1, L_2, L_4, L_5 in parallel, while inductor L_3 is charged by input source alongside capacitors C_1 and C_2 . Diodes D_1, D_2, D_4, D_5 are forward-biased, whereas D_3, D_6, D_B, D_Z are reverse-biased. Voltage across inductors is represented as follows,

$$V_{L4,on} = V_{L5,on} = V_{L1,on} = V_{L2,on} = V_{in}$$

$$V_{L3,on} = V_{in} + V_{CZ} + V_{CB} - V_{out} \quad (1)$$

Here, V_{in} and V_{out} represent the voltages at the input and output terminals, respectively. $V_{L1,on}, V_{L2,on}, V_{L3,on}, V_{L4,on}, V_{L5,on}$ denote the voltages across the inductors L_1, L_2, L_3, L_4, L_5 during mode-1. Additionally, V_{CZ} is the voltage across capacitor C_Z , while V_{CB} is the voltage across capacitor C_B .

Mode 2: (S_1 and S_2 are OFF)

In this mode, switches are deactivated (turned OFF), causing inductors L_1, L_2, L_4, L_5 to discharge in series. During this phase, input voltage source, along with inductors L_1, L_2, L_4, L_5 to supplies energy to the capacitors C_1 and C_2 , which are

charged in parallel. Additionally, the inductors L_1, L_2, L_3, L_4 , and L_5 deliver energy to the components R and C . The diodes D_1, D_2, D_4, D_5 become reverse-biased, while diodes D_3, D_6, D_B, D_Z are forward-biased. The voltages across the inductors are as follows:

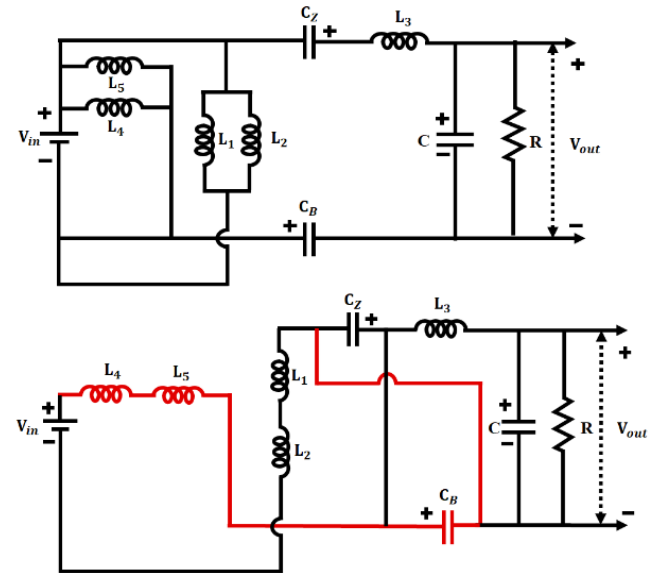


Figure 3: Hybrid boost-zeta converter modes of operation.

$$V_{L4,off} = V_{L5,off} = V_{L1,off} = V_{L2,off}$$

$$= \frac{V_{in} - V_{CZ}}{4} = \frac{V_{in} - V_{CB}}{4} \quad (2)$$

$$V_{L3,off} = V_{CZ} - V_{out} = V_{CB} - V_{out} \quad (3)$$

Here,

$V_{L1,off}, V_{L2,off}, V_{L3,off}, V_{L4,off}, V_{L5,off}$ denote the voltages across the inductors L_1, L_2, L_3, L_4, L_5 , respectively, during mode-2. The voltages across the intermediate capacitors C_Z and C_B are given as follows,

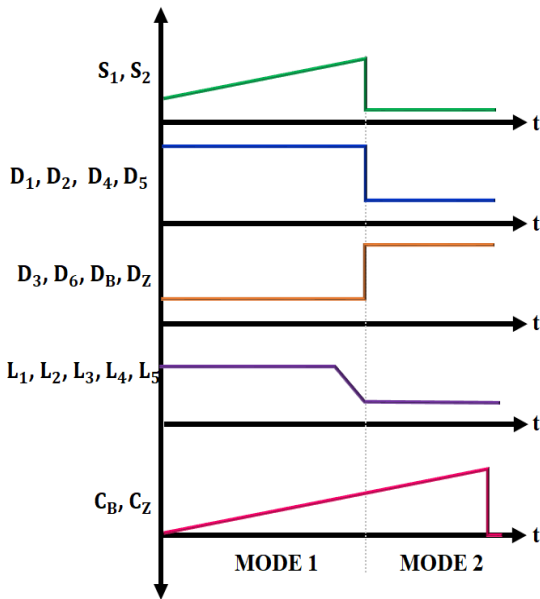
$$V'_C = V_{CZ} = V_{CB} \quad (4)$$

In steady-state conditions, average voltage across an inductor becomes zero, leading to following expression:

$$\begin{aligned} \langle V_{L1} \rangle &= \langle V_{L2} \rangle = \langle V_{L3} \rangle = \langle V_{L4} \rangle \\ &= V_{in}d + \left(\frac{V_{in} - V'_C}{4} \right) (1 - d) = 0 \end{aligned} \quad (5)$$

$$\langle V_{L3} \rangle = (V_{in} + 2V'_C - V_{out})d + (V'_C - V_{out})(1 - d) = 0 \quad (6)$$

The timing diagram of the hybrid boost-zeta converter is given in Figure 4



Here, d represents the duty cycle. Based on equation (6), the voltage V'_C , which corresponds to the voltage across the capacitors C_Z or C_B , is derived as follows,

$$V'_C = \frac{V_{out} - V_{in}d}{1+d} = \frac{1+3d}{1-d} V_{in} \quad (7)$$

By utilizing equations (5) and (7), the expression for voltage gain is derived as follows,

$$V_{M,CCM} = \frac{V_{out}}{V_{in}} = \frac{1+5d+2d^2}{1-d} \quad (8)$$

Thus, input DC supply voltage is enhanced by bidirectional boost-zeta converter.

3.2 Bidirectional Converter

Bidirectional DC converter is integrated, in which the converter operates in two modes: buck and boost is given in fig.5. For bidirectional operations, the diode are replaced with controlled switches. In Buck mode (forward operation), switch S_1 is activated, while in Boost mode (backward operation), switch S_2 is engaged. The operating mechanism of converter is outlined as follows:

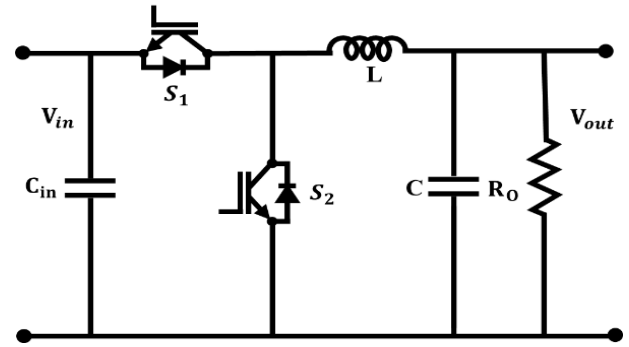


Figure 5: Bidirectional DC-DC converter circuit diagram.

3.2.1 Buck Mode

In Buck mode, output voltage remains lower than input voltage. Battery charging process from DC grid begins with switch S_1 activated while switch S_2 remains off. When switch S_1 is active, input current increases, passing through S_1 and the inductor L . Once switch S_1 is deactivated, current through inductor decreases until next cycle. During this period, energy accumulated in inductor L is utilized to charge battery.

3.2.2 Boost mode

In Boost mode, output voltage exceeds input voltage. During this mode, battery supplies power to load by activating switch S_2 while switch S_1 remains turned off.

When switch S_2 is activated, input current increases and flows through inductor L and switch S_2 . Once switch S_2 is deactivated, current

in the inductor decreases until next cycle begins. During this period, energy accumulated in inductor L is transferred to load.

3.3 PI Controller

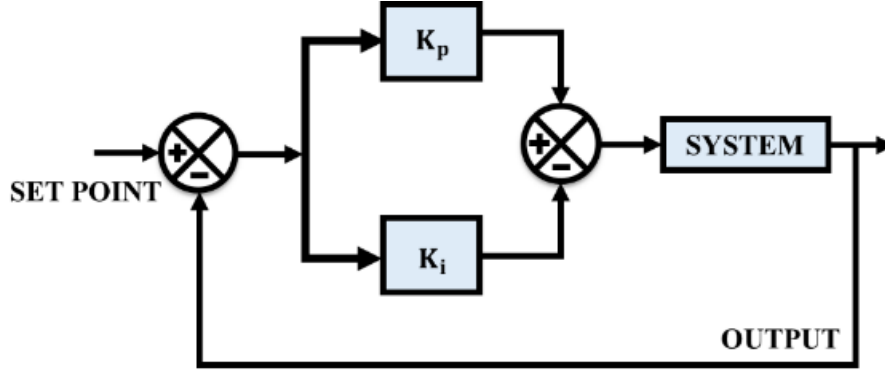


Figure 6: PI controller.

The control signal for the PI controller is defined as follows:

$$U = K_p + K_i \int \Delta dt \quad (9)$$

$$C(S) = K_p + \frac{K_i}{s} \quad (10)$$

The standard procedure for PI tuning involves the following steps:

1. Initially, set the integration gain to zero.
2. Gradually increase K_p until satisfactory results are achieved.
3. Introduce the integration gain and fine-tune K_i until the steady-state error is eliminated.

PI controller regulates bidirectional Boost-Zeta converter by maintaining a constant DC-link voltage at its output. Fig. 6 shows a closed loop PI controller.

The PI controller ensures the regulation of Boost-Zeta converter by maintaining a stable DC link voltage at its output. This regulated voltage is then transmitted to the grid with the help of a single-phase VSI.

3.3 Single Phase VSI

The single-phase VSI takes output from bidirectional Boost-ZETA converter as its input, converting steady DC link voltage into an AC voltage. Proposed inverter configuration features two switches S_1, S_2 and utilizes a PWM generator to produce pulses. Furthermore, through grid synchronization, the VSI's AC output is transferred to grid. Figure 7 depicts circuit diagram for the 1Φ VSI.

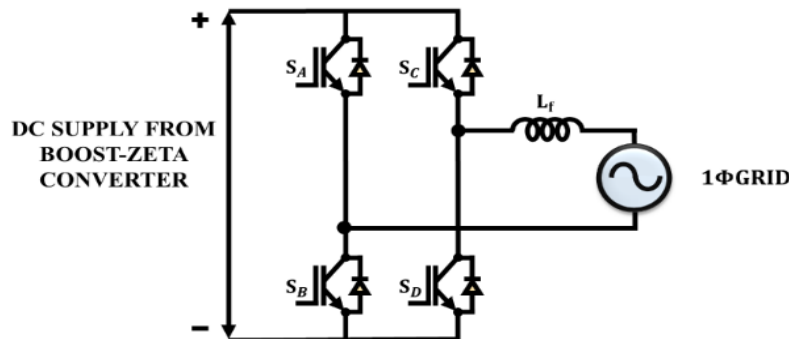


Figure 7: Single phase VSI.

A PI controller is utilized to compare actual power with reference power, ensuring grid synchronization. By appropriately adjusting frequency, voltage, and phase angle,

synchronization is achieved, enabling VSI to deliver high-quality AC electricity to grid. As a result, electric vehicle receives a consistent charge from PV system while performing its intended

tasks. Based on proposed approach, EV maintains a continuous energy supply either directly from PV system or, when PV panel generates surplus energy, this is routed to grid via boost converter. In event of PV failure, EV draws energy from grid through Zeta converter, which operates in buck mode for this purpose. Consequently, proposed system offers improved voltage gain, reduced total harmonic distortion (THD), enhanced reactive power compensation, and an uninterrupted power supply

4. Result and Discussion

The implementation of the proposed bidirectional boost-zeta converter for Battery Storage Based Grid Tied EV Traction System been carried out

using the MATLAB platform, and the resulting outcomes are thoroughly analyzed and discussed in the following sections.

Table 1: Parameter Specifications.

Parameter	Specifications
PV System	
Rated Power	10kW
No. of panels connected in series	5
No. of panels connected in parallel	8
Short circuit current	8.35A
Open circuit voltage	37.25V
Hybrid Boost-Zeta converter	
Inductor	1mH
Capacitor	22 μ F
Switching Frequency	10kHz

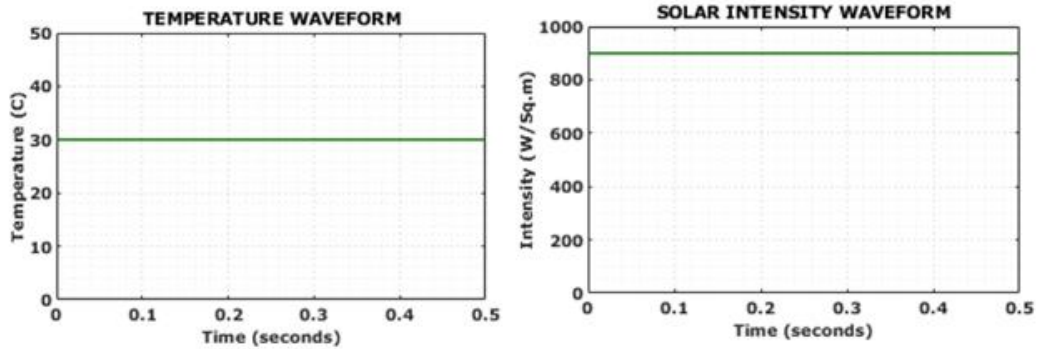


Figure 8: Temperature and intensity waveform.

Figure 8 presents the solar panel temperature and intensity waveform. Figure.8. (a). Shows the temperature waveform of PV system. The temperature is maintained constant at a temperature of 30°C throughout the system.

Figure.8 (b) shows the PV panel intensity waveform. A constant solar intensity value of 900 W/sq.m. is attained in the entire system, ensuring stable input from the PV system.

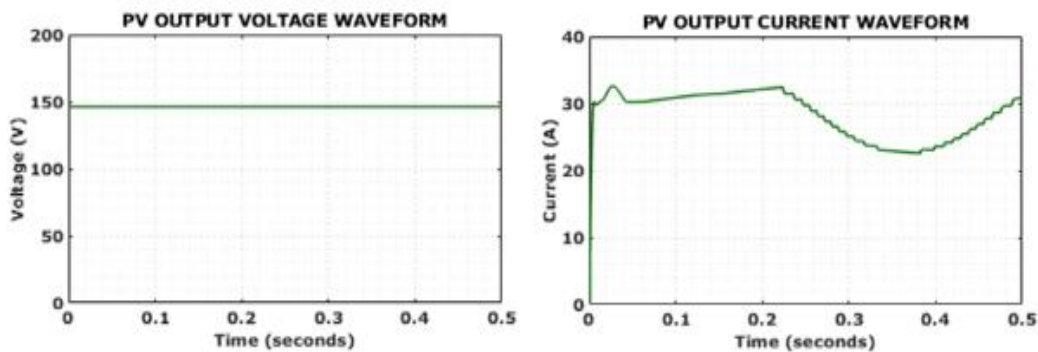


Figure 9: PV output waveform.

Figure 9 represents output waveform of PV system. Figure 9 (a) shows output voltage waveform of PV system. Output voltage remains

consistent at 148 V. Figure 9 (b) shows output current of PV system. Waveform displays significant variations, beginning at

approximately 30A, rising to about 33A, and subsequently oscillating within the range of 23A to 33A. These variations imply changes in power

requirements or the operational phases of the battery storage system, such as charging and discharging cycles

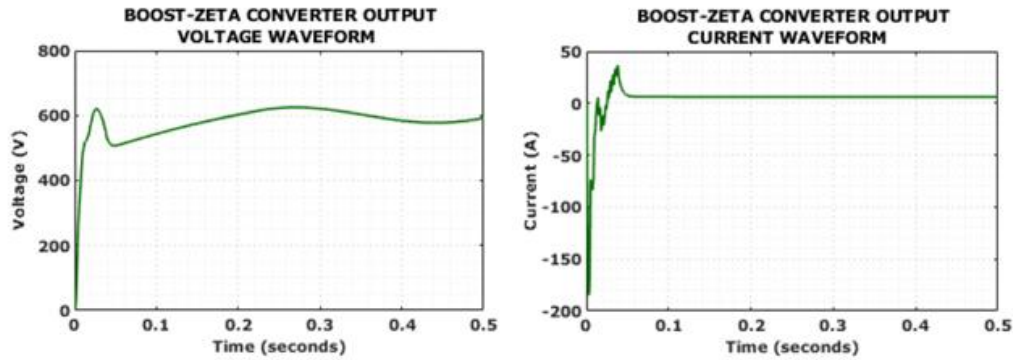


Figure 10: Boost-zeta converter.

Figure 10 displays the proposed converter output waveforms. Fig.10 (a) shows output voltage waveform of hybrid boost-zeta converter. After initial fluctuations, voltage gets stabilized around

600V with few fluctuations. Fig.10 (b) shows output current waveform of converter. At initial phase, current rises to 40A and then stabilizes around 8A.

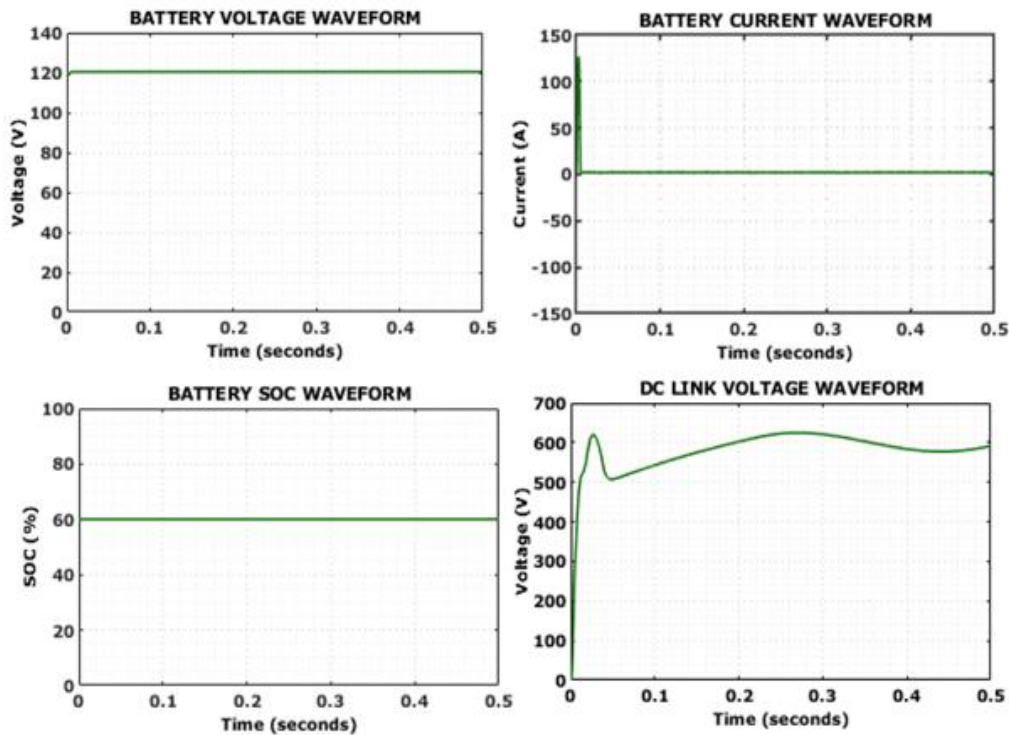


Figure 11: Battery waveform.

Figure 11 visualizes the battery waveform. Figure 11. (a) shows the voltage waveform of the battery, it is constantly maintained at 120V. Figure 11. (b) shows the battery current waveform. After initial sudden rise, the battery is stabilized with reduced current flow. Figure 11. (c) shows the Battery State

of Charge (SOC) waveform. The battery's SOC remaining constant at 60% throughout the system indicating minimal charging or discharging activity. Figure 11. (d) shows the voltage waveform of DC link. The voltage is settled at 600V after minimum fluctuations.

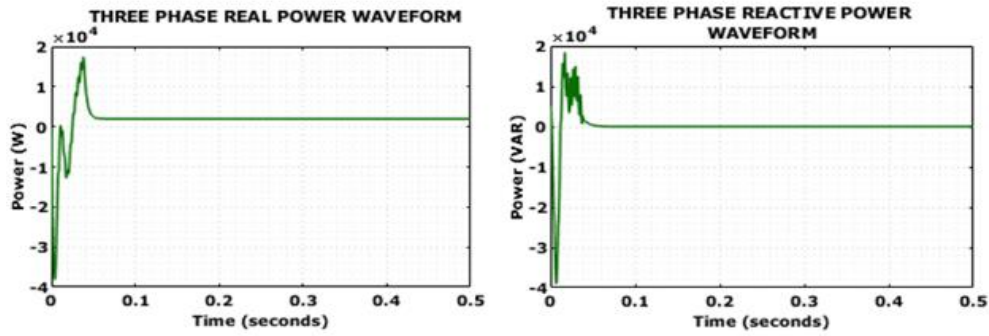


Figure 12: Real and reactive power waveforms.

Figure 12 illustrates 3 Φ real and reactive power waveforms. Figure 12. (a) shows the real power waveform, with initial transient spike, the power

gets constant around 0.5×10^4 . Figure 12. (b) shows the reactive power waveform, after sharp peak in the initial phase the power gets stabilized.

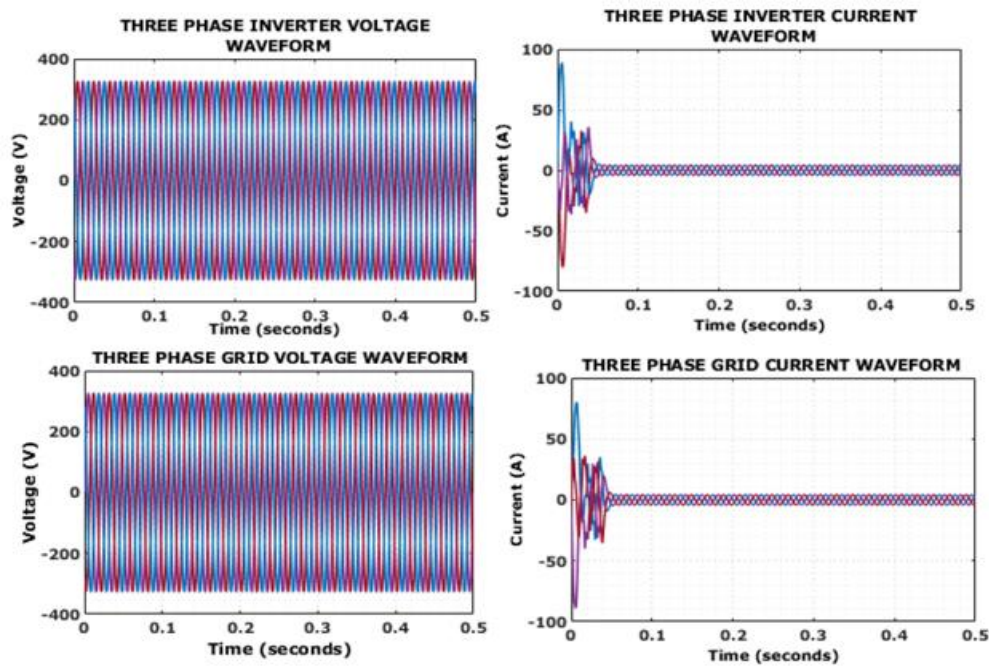


Figure 13: 3 Φ Inverter and grid waveforms.

Figure 13 demonstrates the 3 Φ inverter and grid waveforms. Fig.13. (a) shows the voltage waveform of the 3 Φ inverter, showing a balanced sinusoidal waveform ranging from $\pm 300V$ over a 0.5s period, signifying correct inverter operation. Fig.13.(b) shows the 3 Φ inverter current waveform, starting with a transient phase ranging from $\pm 100A$, followed by stabilization in a steady-state with low amplitude between $\pm 10A$. Fig.13.(c) shows the 3 Φ voltage waveform of the grid, it is constantly maintained at $\pm 300V$. Fig.14.(d) shows the current waveform of 3 Φ grid, after initial fluctuations the current is constantly maintained at $\pm 10A$.

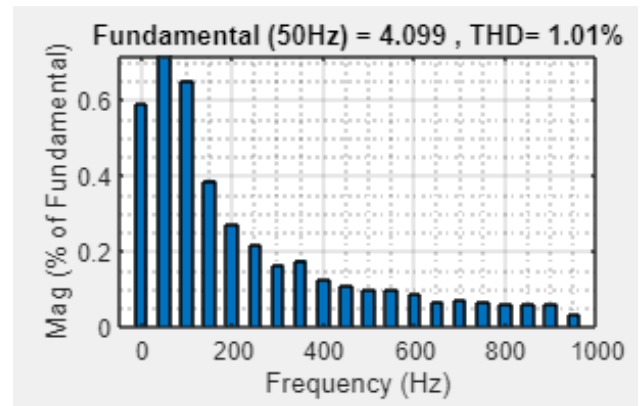


Figure 14: THD waveform.

Figure 14 reveals the THD waveform. The graph shows effective harmonic suppression in a bi-directional boost-zeta converter for a grid-tied EV

system, evidenced by low Total Harmonic Distortion of 1.01% and diminishing higher-order harmonics, ensuring improved power quality and efficiency.

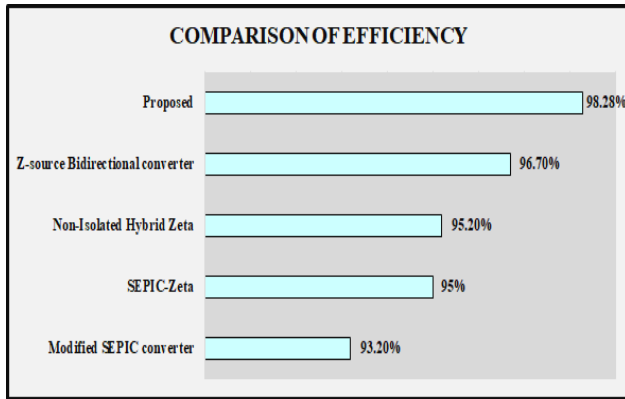


Figure 15: Comparison of Efficiency.

Figure 15 exhibits the comparison of efficiency of proposed converter with existing converter topologies. From the graph, it shows that proposed converter attains the highest efficiency of 98.28% outperforming other converters.

Table.2 Comparative Analysis of voltage gain.

Converter	Voltage gain
Zeta [15]	11.02
Modified SEPIC converter [14]	12.5
Proposed	15.4

Table 2 shows the voltage gain comparative analysis of converters. The proposed bidirectional hybrid boost-zeta converter attains enhanced voltage gain of 15.4%.

5. Conclusion

This paper introduces a novel bi-directional boost-zeta converter for battery energy based EV traction system. Thus, the proposed bi-directional boost-zeta converter ensures efficient energy exchange between the battery and DC link during both charge and discharge cycles. The control system maintains DC link voltage and grid parameters, guaranteeing stability and smooth grid integration. This design provides to EV traction needs while utilizing battery storage for grid support. Additionally, the single-phase voltage source inverter (VSI) facilitates the conversion of DC power to AC power, offering a cost-effective solution while minimizing energy losses.

Harmonic distortion in the circuit is mitigated using an LC filter. The expected outcomes are validated through MATLAB simulations. Consequently, the proposed converter delivers a high voltage gain ratio of 15.4 and an efficiency of 98.28%, making it a superior choice for EV traction applications compared to conventional converters.

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