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Article

Closed loop battery current controlled zeta converter for improved power quality in electric vehicle charging stations

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Abstract: To encourage an eco-friendly environment and pollution-free transportation, most of the automobile industries are promoting electric vehicles. However, with the adoption of electric vehicles, various power quality problems are encountered mainly during vehicle battery charging. Thus, this research work focuses on power quality improvement in electric vehicle battery charging stations. In this article, a closed-loop battery current-controlled zeta converter with a PI controller is introduced to achieve quality power to charge electric vehicles. The proposed converter enhances the overall performance of the system by reducing voltage fluctuations, harmonic content, and frequency variations. Besides, this suggested closed-loop battery-controlled zeta converter improves the power factor and overall efficiency of the system. In the proposed scheme, the vehicle battery current feedback to the PI controller generates the switching pulses, thereby generating the desired duty ratio to operate the converter to maintain a constant current. The entire system is implemented in MATLAB/Simulink and various power quality parameters namely voltage and current characteristics, active and reactive power characteristics, frequency, total harmonic distortion (THD), power factor, and efficiency are measured. The conventional buck converter produces voltage THD of 35.85%, current THD of 41.81%, power factor of 0.8, and efficiency of 72.2%. The conventional zeta converter produces voltage THD of 9.07%, current THD of 12.7%, power factor of 0.95, and efficiency of 91.0%. In both the cases, voltage and current THDs are violating the IEEE 519 standard. To validate the usefulness of the proposed zeta scheme, it is compared with conventional buck and conventional zeta converter-based charging stations. From the results, it is found that the proposed closed-loop battery current-controlled zeta converter charging station produces improved power quality characteristics over conventional methods. It achieved a voltage THD of 4.93%, current THD of 1.9%, power factor of 0.96, and efficiency of 91.8%. The voltage THD and current THD greatly adhere to the permissible limits of 5% and 8% that are defined by IEEE 519, which are far better than the conventional buck and zeta models.

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1. Introduction

The day-by-day increased use of automobiles creates a lot of environmental and safety issues. For instance, India boasts the second-largest road transport network in the world, which carries 90% of all passenger traffic as well as 64.5 percent of all commodities in the nation. In India, there are about 78,000 petrol bunks, and the country's road transport industry uses 44,92,000 barrels of oil daily, producing 2.46 billion metric tonnes of carbon dioxide, alternatively, 6.8% of global emissions [1, 2]. To reduce the dependency on traditional automobiles, electric vehicles (EVs) are fairly a recent concept in the transportation industry. EVs play a significant role in curbing carbon emissions to address global warming. Transitioning to EVs wouldn't just eradicate transportation emissions; it would also bolster energy efficiency, decrease dependence on fossil fuels, and enhance air quality by reducing air pollution [3]. Considering these advantages, there were 3 million electric vehicles on the road in 2017 in India. Moreover, it is predicted to rise this number to 228 million by 2030 [4, 5]. However, to prepare for such evolution in e-mobility, a strong charging infrastructure has to be deployed.

Thus, as the number of EVs rises worldwide and will continue to rise in the future, it is crucial to create a substantial network of charging infrastructure, for which the energy and transportation sectors must be integrated [6]. However, the forecast of future smart grids integrated with EV charging stations has prompted severe worries regarding all elements of power system quality [7, 8]. The harmonic voltage levels of the power distribution system are negatively impacted by the widespread use of electric vehicle battery charging units. Thus, to deliver high-quality electricity to the end-user, the connection of the charging infrastructure with the electric network became a considerable barrier [9].

Rechargeable batteries offer several advantages over traditional disposable batteries, including cost savings, reduced waste, and convenience. Nonetheless, to fully capitalize on these advantages, it is imperative to utilize a top-tier battery charger meticulously engineered to be compatible with the precise rechargeable battery variant in use. Battery chargers come in various types, including plug-in chargers, USB chargers, and solar chargers. The most common type of charger for rechargeable batteries is a plug-in charger, which plugs into a wall outlet and uses an electrical current to recharge the battery [10]. The non-linear behavior of switching power components can lead to several challenges in the design and operation of battery chargers. The charger's output voltage and current can fluctuate rapidly, leading to instability and reduced charging efficiency. In addition, non-linear behavior can result in electromagnetic interference, which can cause problems with other electronic devices [11]. The high harmonic components generated by EVs can have a negative effect on the electrical network and related equipment. Power quality standards have been developed to limit the amount of harmonic distortion that can be present in electrical systems and help ensure the reliable and efficient operation of the electrical network. Both single-phase and three-phase power supply systems can be used to power electric vehicles, where a three-phase system can provide a faster charging experience. However, due to the wider availability of single-phase power supply points, most electric vehicle chargers are designed to work with this system [12]. The non-linear loads such as EV chargers can also increase power losses in distribution transformer windings and reduce power output, further affecting the power quality of the distribution network. Therefore, the connection of EV chargers to the power grid or distribution network can have a substantial impact on power quality [13, 14].

These power quality issues cause various problems in electrical systems, affecting the efficiency and reliability of equipment. There are several methods developed to mitigate power quality issues [15–20]. Specifically, EV chargers are designed with buck converters in the literature [21]. But, in such designs, the efficiency of the converter is determined to be very low. Along with low efficiency, the ripple in the output voltage is higher which damages the EV battery pack. The power factor and efficiency improved with the zeta converter are discussed in [22, 23], and also used for multi-output applications [24]. It effectively minimizes conduction and switching losses and improves the power quality [25–27]. Later, zeta converters are used as a potential alternative to buck converters in EV charging applications. The zeta converter holds significant promise as an efficient and versatile solution for EV charging systems [28,29]. However, due to a lack of feedback control mechanisms, these zeta converters face significant challenges in precise battery state of charge control, which potentially leads to overcharging or undercharging. This reduces battery lifespan and efficiency.

Thus, to address the abovementioned issues with EV charging stations, this paper proposes a closed-loop battery current-controlled zeta converter as a subsequent enhancement to the conventional zeta converters. This proposed design improves the power quality on both the grid side and the load side when compared to the traditional buck and zeta converters. Functioning at an exceptionally high frequency, the closed-loop battery current-controlled zeta converter significantly diminishes output voltage ripple, consequently improving system performance. Leveraging the converter's capacity, enhances the power factor of the grid, leading to a reduction in reactive power consumption. The harmonics within the voltages experience a reduction to levels even lower than those achievable with both conventional buck and zeta converters. With this improvement, the proposed converter attains lower voltage and current total harmonic distortion (THD) levels, better power factor, and efficiency, rendering it highly suitable and recommended for electric vehicle battery charging applications.

The contributions of this paper are outlined as follows:

- A control strategy was implemented between the EV battery and zeta converter to adjust the duty cycle continuously.
- Zeta converter, battery, and PI controller connections in a charging station create better voltage regulation.
- The feedback mechanism was implemented with the PI controller to achieve precise battery current control.

The paper is structured as follows. Section 2 provides an elaboration of the construction of the proposed model and a detailed exploration of the battery current control mechanism. Section 3 presents a comprehensive depiction of the MATLAB simulation results along with a meticulous comparative analysis between the conventional and proposed schemes. Finally, Section 4 encapsulates the conclusions by wrapping up the paper succinctly and effectively. Hereafter, the proposed closed-loop design of the zeta converter is referred to as the "proposed ZETA converter" and the open-loop design of the zeta converter is referred to as the "conventional ZETA converter".

2. Design and Implementation of the Proposed Charging Station

To develop the proposed charging station, a PI-controlled feedback-based zeta converter is implemented in this research work. The control strategy and feedback mechanism are the key differences between conventional and proposed systems. The key difference is as follows in terms of control strategy and feedback mechanism. In a conventional system, the control strategy typically involves fixed duty cycle or pulse width modulation (PWM) control. This means that the duty cycle of the switching devices (MOSFET/IGBT) is adjusted based on the input voltage (V_s), desired output voltage (V_{dc}), and load/battery current. In this case, the output voltage regulation relies on the accuracy of the duty cycle and input voltage, which is not helpful according to real-time dynamic load variations.

To address this issue, in the proposed system, a closed-loop battery current control strategy is implemented with a PI controller that continuously monitors the load/battery current and adjusts the duty cycle (D) of the proposed converter MOSFET switch to maintain the desired output current (I_{bat}). The feedback mechanism with a PI controller in the zeta converter of an EV enhances power quality. It ensures that the load/battery current remains close to the reference current, which can help achieve precise

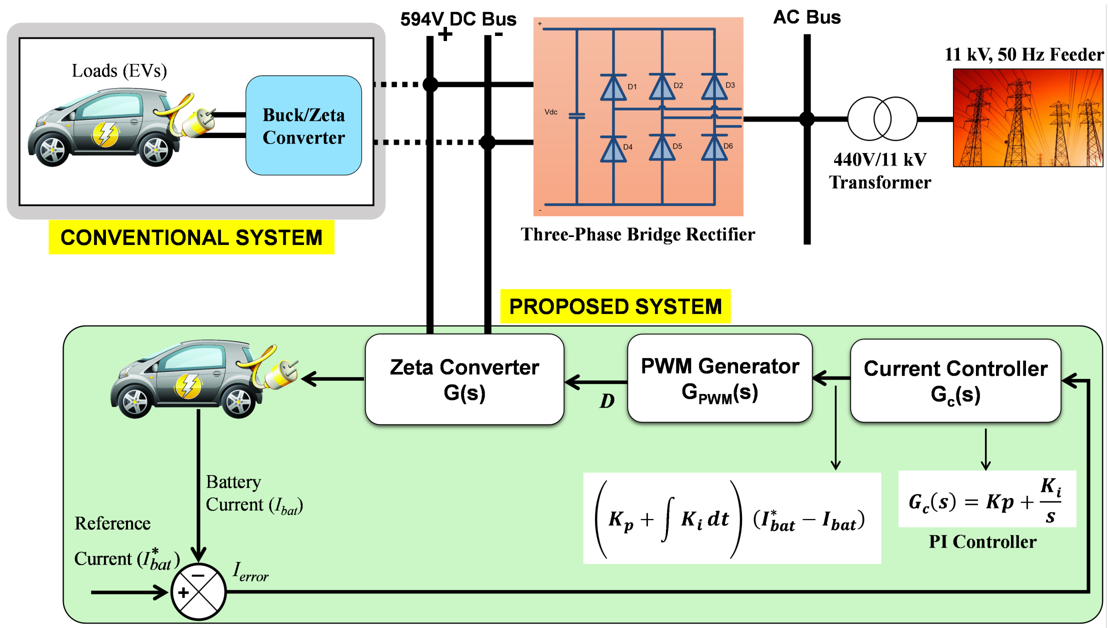


Figure 1. Proposed and conventional zeta converter charging station.

control of current and, consequently, better control of the output voltage and charging/discharging of the EV battery. It further corrects the power factor, reducing voltage fluctuations, and mitigating harmonics. This approach protects the EV battery, improves efficiency, and ensures grid compatibility.

The conventional converter is replaced with a zeta converter with an EV battery current control scheme, as shown in Figure 1. The proposed model represents the closed-loop EV battery current-controlled zeta converter charging system. It starts with an 11 kV feeder, the primary power source, which is then reduced to 440V via an 11 kV/440V transformer. The rectifier receives alternating current (AC) 440V from the transformer and converts it to direct current (DC) 594V. Further, the proposed zeta converter step-down to DC 60V to charge the vehicle battery. To manage this process efficiently, the zeta converter dynamically controls the voltage supplied to the EV battery. The PI controller regulates the charging current to maintain consistency and account for variations and disturbances in the system. This setup ensures the safe and effective charging of the EV battery. For modelling and simulation, the EV battery specifications are considered as 60V, 14 Ah EV in this paper.

Similar to the buck converter, the proposed zeta converter also has only one MOSFET switch for controlling the output voltage. The proposed zeta converter consists of an LC network to transfer power between the input and battery. It offers effective voltage regulation, ensuring that the EV battery receives the required charging voltage within tight tolerances. The zeta converter's inherent characteristics help minimize voltage and current harmonics, resulting in improved power quality during charging, which is crucial for maintaining the health and longevity of EV batteries.

The circuit structure of the zeta converter can be observed in Figure 2. Here, C_f is the input filter capacitance, L_i is the input inductor, C_1 is the intermediate capacitance, L_o is the output inductor and C_d is the output capacitance. The passive element values are calculated with respect to input and output voltages (V_s and V_{dc}), power rating (P), switching frequency(f_s), and duty ratio (D). The duty cycle is calculated from Equation (1) as

$$D = \frac{V_{dc}}{(V_s + V_{dc})}. \tag{1}$$

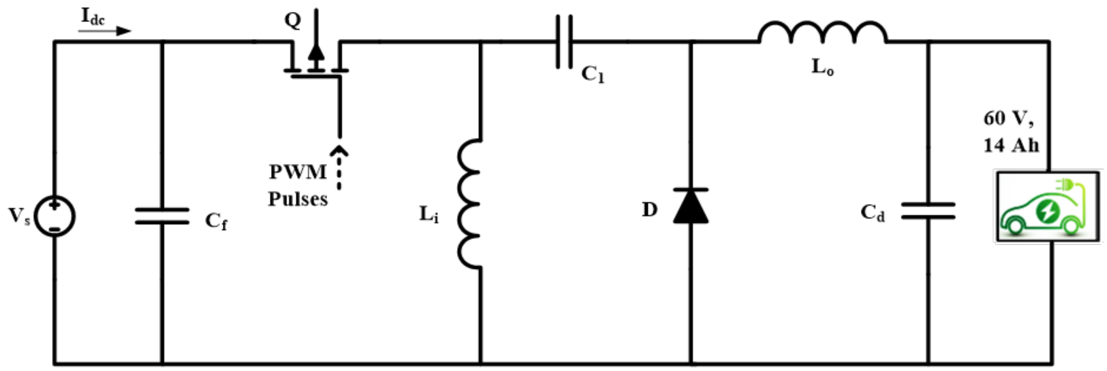


Figure 2. EV connected zeta converter.

The inductor and capacitor equations are obtained based on the ON and OFF states of the converter MOSFET switch. During ON state the inductor L_i is charged by the converter input voltage, C_1 is charged by the inductor L_i current, inductor L_o is charged by the C_1, and Cd supplies current to the battery. During the OFF state, the inductor Li is discharged through C_1, and Lo discharges into Cd and the battery. The formulas related to the design of the circuit parameters are adopted from [30, 31] and these are shown in Equations (2) to (5),

$$L_i = \frac{DV_s}{f_s \times \Delta i_{L_i}}, \tag{2}$$

$$L_o = \frac{(1-D)V_{dc}}{f_s \times \Delta i_{L_o}}, \tag{3}$$

$$C_1 = \frac{D \times I_{dc}}{f_s \times \Delta V_{C_1}}, \tag{4}$$

$$C_d = \frac{I_{dc}}{2\omega \times \Delta V_{dc}}, \tag{5}$$

where Δi_{L_i} and Δi_{L_o} are the permitted ripple currents of inductors L_i and L_o respectively. Δi_{L_i} and ΔV_{dc} are the the permitted ripple voltages of capacitors C_1 and C_d respectively. I_{dc} is the input DC to the converter.

Zeta converter can operate in two modes of operation, In Mode-1 MOSFET switch is ON and in Mode-2 MOSFET switch is OFF. Following the general state space model representation given by Equation (6), the state space model of the zeta converter is derived as given in Equations (7) to (16) corresponding to the ON and OFF operations of the MOSFET.

$$\left.\begin{aligned} \bar{X} &= AX + BU \\ Y &= CX + DU \end{aligned}\right\}, \tag{6}$$

where, $\bar{X}$ is the differential state vector, A is the system matrix, X is the state vector comprising the variables x_1, x_2, x_3, x_4, B is the input matrix, U is the input vector, Y is the output vector, C is output matrix, D is input matrix.

- Mode-1: Switch is ON (Q-ON) as shown in Figure 3, both L_i and L_o are charging during this interval (DT).

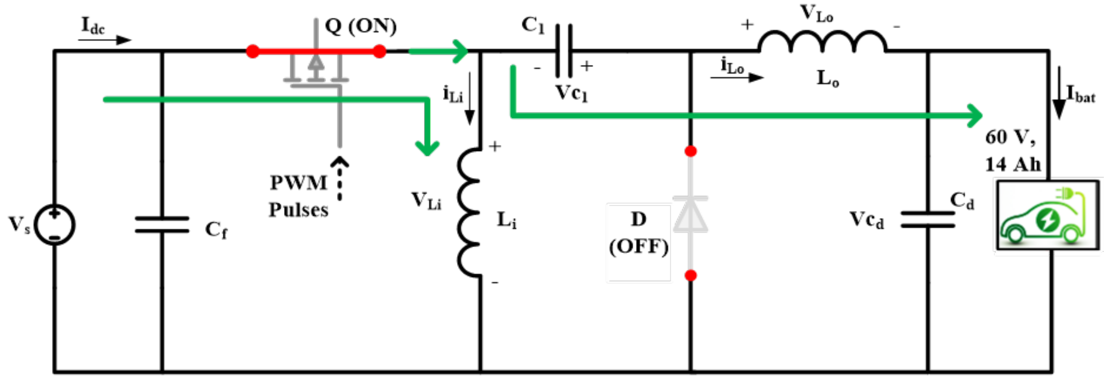


Figure 3. Current flows during the switching ON state of EV connected zeta converter.

Let us consider, $i_{L_i} = x_1, i_{L_o} = x_2, V_{C_1} = x_3, V_{C_d} = x_4$, thereby the system equations can be expressed as Equations (7) to (10) corresponding to the ON state of the MOSFET.

$$\frac{di_{L_i}}{dt} = \frac{V_s}{L_i} \tag{7}$$

$$\frac{dV_{C_1}}{dt} = -\frac{i_{L_0}}{C_1} \tag{8}$$

$$\frac{di_{L_o}}{dt} = \frac{V_{C_1}}{L_o} + \frac{V_s}{L_o} - \frac{V_{C_d}}{L_o} \tag{9}$$

$$\frac{dV_{C_d}}{dt} = \frac{i_{L_o}}{C_d} - \frac{V_{C_d}}{R_i C_d} \tag{10}$$

- Mode-2: Switch is OFF (Q-OFF) as shown in Figure 4, both L_i and L_o are discharging during this interval (1-D)T, and transform their stored energy into C_1 and C_d respectively. Thus, the system equations can be expressed as Equations (11) to (14) corresponding to the OFF state of the MOSFET.

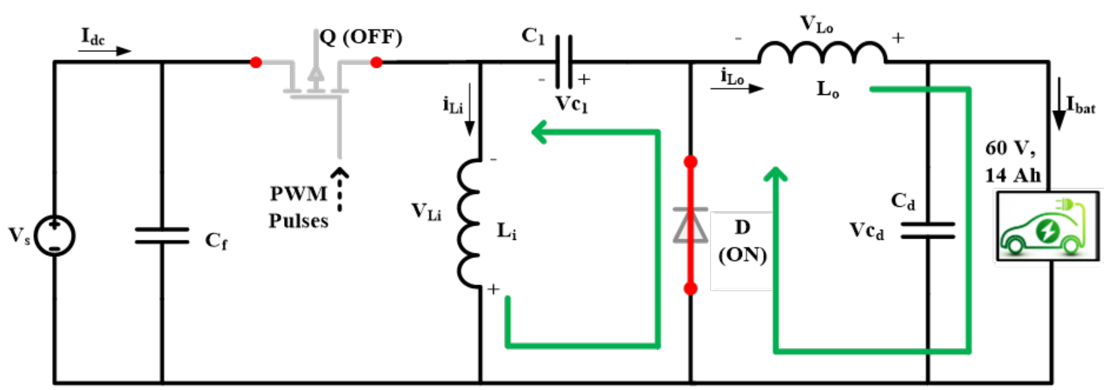


Figure 4. Current flows during the switching OFF state of EV connected zeta converter.

$$\frac{di_{L_i}}{dt} = -\frac{V_{C_1}}{L_i} \tag{11}$$

$$\frac{dV_{C_1}}{dt} = -\frac{i_{L_i}}{C_1} \tag{12}$$

$$\frac{di_{L_o}}{dt} = -\frac{V_{C_d}}{L_o} \tag{13}$$

$$\frac{dV_{C_d}}{dt} = \frac{i_{L_o}}{C_d} - \frac{V_{C_d}}{R_i C_d} \tag{14}$$

The output of the zeta converter is given as Equation (15). The above-mentioned ON state and OFF state equations are combined using the state space averaging technique, thereby forming the final state space model of the zeta converter as Equation (16).

$$V_o = \frac{DV_s}{(1-D)} \tag{15}$$

$$\left.\begin{aligned} \begin{bmatrix} \bar{x_1} \\ \bar{x_2} \\ \bar{x_3} \\ \bar{x_4} \end{bmatrix} &= \begin{bmatrix} 0 & 0 & (1-D)/L_i & 0 \\ 0 & 0 & D/L_o & -1/L_o \\ (1-D)/C_1 & -D/C_1 & 0 & 0 \\ 0 & 1/C_o & 0 & -1/R_iC_o \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} D/L_i \\ D/L_o \\ 0 \\ 0 \end{bmatrix} [U] \\ [Y] &= \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix}^T \end{aligned}\right\} \tag{16}$$

2.1. Design Procedure of Proposed System

The proposed system has been incorporated into the zeta converter by integrating a closed-loop control system for regulating battery current during charging. This controlled methodology for managing battery current is instrumental in achieving a significant reduction in harmonics within the system. The operationalization of the closed-loop battery current control mechanism is visually depicted in Figure 5.

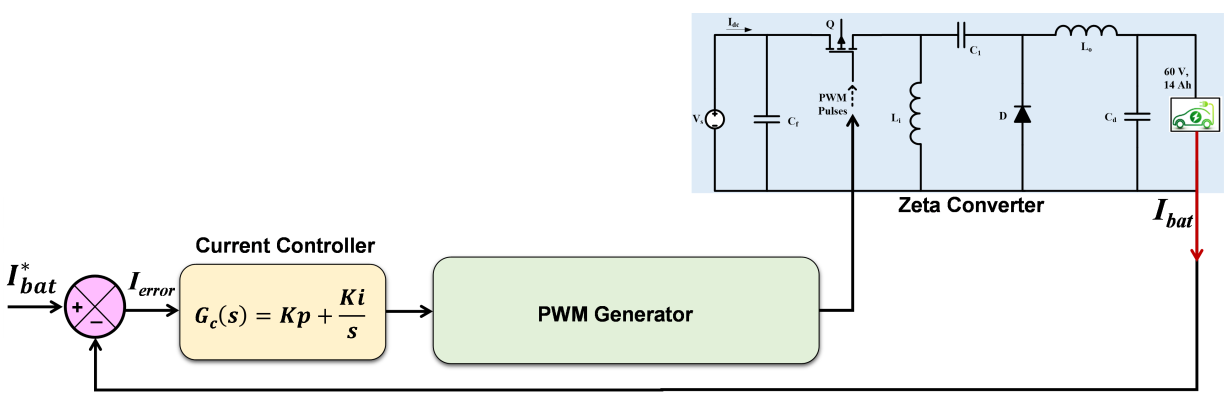


Figure 5. Proposed zeta converter with the closed loop battery current controller mechanism.

The battery current control system utilizes a PI controller to regulate and stabilize the charging process, The proportional term of the controller responds to the difference between the desired battery current reference (I^*_{bat}) and the actual battery current (I_{bat}). It generates a control signal that is proportional to this error and the integral term accumulates the historical error and generates a control action that helps eliminate steady-state errors. This proposed closed-loop current controller is useful for maintaining accurate and consistent battery current regulation. The combined output of the proportional and integral terms determines the corrective action applied to the system.

This output signal is used to adjust the duty cycle of the zeta converter, influencing the current flowing into the battery. The proportional and integral coefficients of the closed-loop current controller namely K_p and K_i are adopted from [32,33]. The corresponding formulas are given to calculate K_p and K_i as shown in Equations (17) and (18) as

$$\frac{K_i}{K_p} = \frac{R_i}{L_i}. \tag{17}$$

$$\left.\frac{I_{bat}\,(s)}{I^*_{bat}}\right|_{CL} = \frac{1}{1+s\tau}, \tag{18}$$

where,

$$\tau = \frac{L_i}{K_p}.$$

The PI controller calculates the control output based on the error signal, which in turn adjusts the duty cycle of the converter. This modulation of the duty cycle controls the energy flow to the battery, ensuring that the battery current closely follows the reference. During this procedure, the functioning of the converter achieves improved stability, consequently resulting in a more pronounced reduction of harmonics. Following are the key benefits of the proposed scheme.

- Improved power quality: The proposed closed-loop battery current control system can ensure that the battery current remains within a predetermined range, resulting in a more stable and consistent charging process. This can lead to improved power quality, with reduced voltage and current distortion, and lower THD.
- Higher efficiency: The proposed model improves the efficiency of the charging process by optimizing the power transfer from the grid to the battery. This can reduce power losses and increase the charging speed of the EV.
- Improved power factor: The proposed model improves the power factor of the EV battery charging station. A higher power factor means that more of the power supplied by the grid is used effectively, resulting in reduced power losses.

3. Simulation Results and Discussions

To design and analyze an effective closed-loop battery current-controlled zeta converter charging station, the system simulation parameters are clearly stated in Table 1.

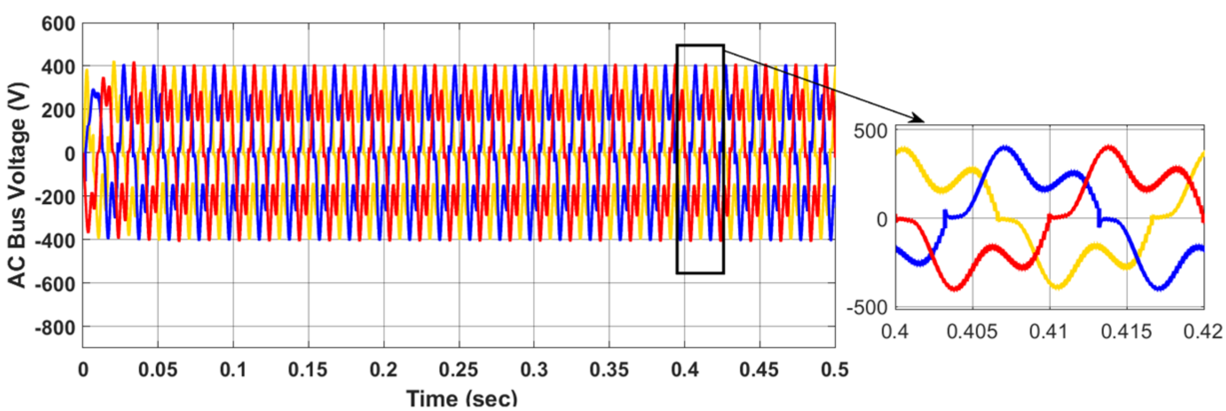
The effectiveness of the proposed closed-loop battery current-controlled zeta converter-based charging station is compared with conventional buck converter and zeta converter-based charging stations. The comparisons are made with respect to various power quality parameters as discussed in the following subsections.

Table 1. Simulation parameters of proposed systems.

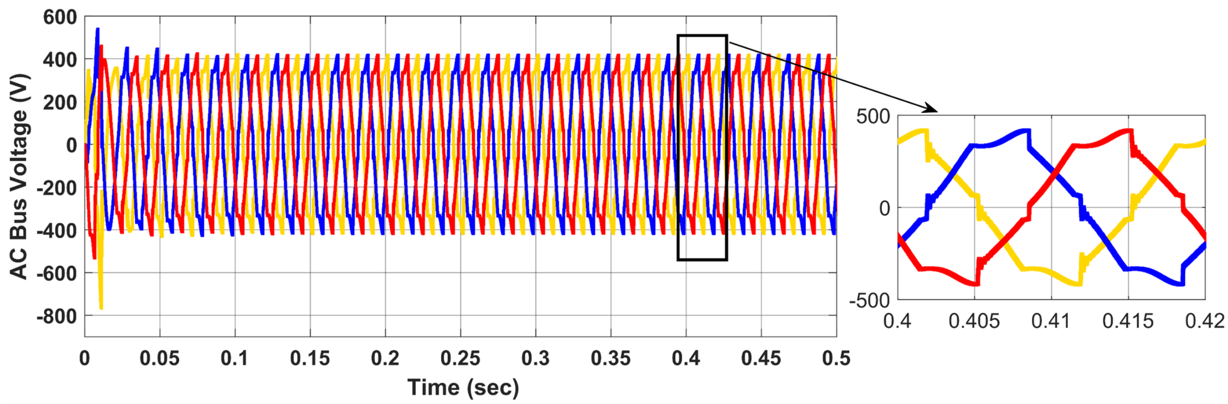
Parameters	**Specifications**
Feeder voltage	11 kV
Step-down transformer	11kV/400V
Zeta converter input voltage	594 V
Switching frequency	100 kHz
Zeta converter output voltage	60 V
Duty cycle D	$0.092 \approx 9.2\%$
Input Inductor L_i	2.73 mH
Output Inductors L_o	2.724 mH
Intermediate Capacitor C_1	3.067 μF
Output Capacitors C_d	30.267 μF
Proportional gain K_p	0.45
Integral gain K_i	5.4
Battery nominal voltage	60 V
Battery rated capacity	14 Ah
Battery charging current	2 A
Battery SoC	20%
Charging temperature range	0°C-45°C

3.1. Voltage Characteristics

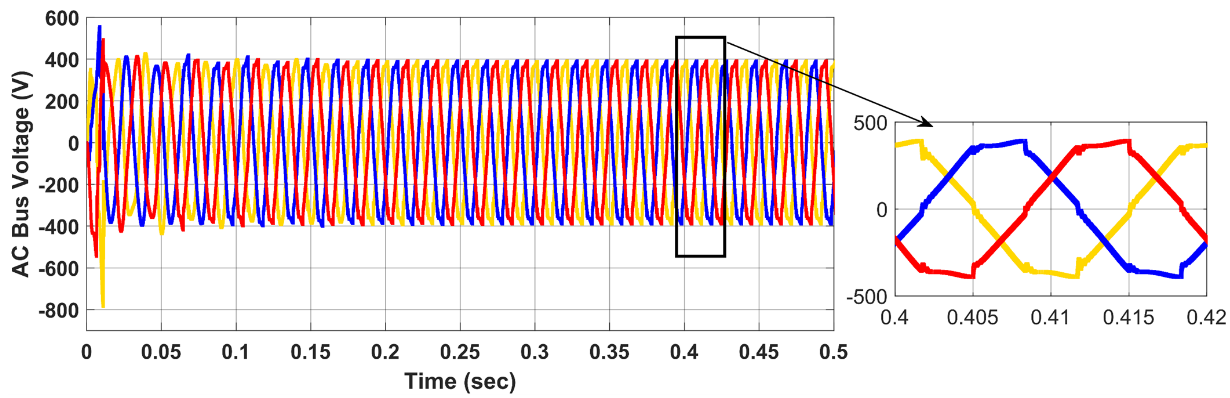
The presence of harmonics in the voltage waveform can lead to increased levels of distortion and can impact the performance of connected devices. Harmonics are multiples of the fundamental frequency and can be caused by a variety of factors, including nonlinear loads like electric vehicle chargers. The harmonic distortion can cause a range of negative effects, including increased power losses, reduced efficiency, and decreased power factor. The simulation results of the conventional and proposed systems are shown in Figure 6a, Figure 6b, and Figure 6c respectively.



(a) With the conventional buck converter.



(b) With the conventional zeta converter.



(c) With the proposed zeta converter.

Figure 6. Charging station's AC bus three-phase voltage characteristics.

From this result, it can be clearly understood that the voltage waveform quality has been significantly improved from the conventional to the proposed converter scheme.

3.2. Power and Frequency Characteristics

Active and reactive power characteristics are plotted to validate the effectiveness of the proposed charging station during the loading. Results given in Figure 7a and Figure 7b compare the conventional and proposed system responses. From these, it is observed that the proposed scheme greatly reduces the power consumption from the charging station on the grid.

Frequency characteristic is one of the important power quality indices that is majorly affected by active power consumption. Any deviation of the frequency from the specified limits destroys the connected load to the system. This problem is further aggravated in the case of EV charging station applications, where battery performance depends on the grid frequency. The frequency characteristics are depicted in Figure 8. As observed in this figure, the frequency is well maintained in the proposed system as similar to the conventional system along with the improvement in power consumption as discussed above. The characteristics show a settling time of 0.25 sec and maintain a 50 Hz grid frequency for the entire operation.

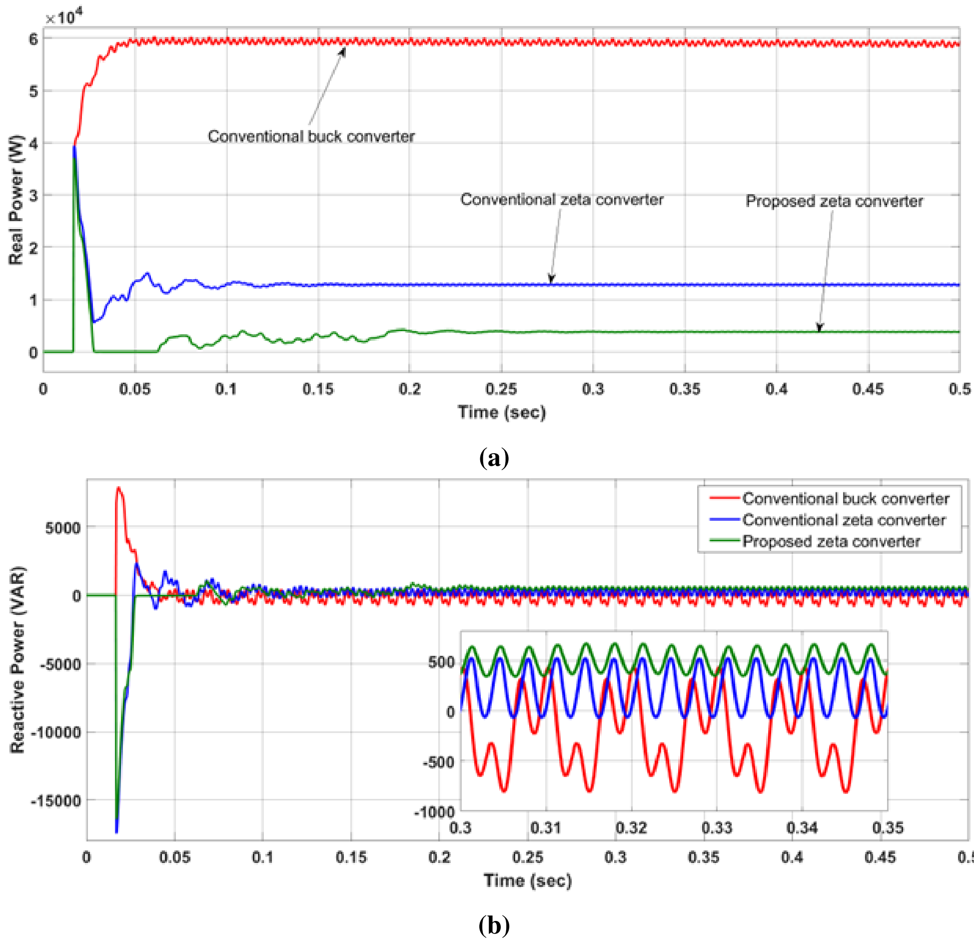


Figure 7. Comparison of conventional buck converter, conventional zeta converter, and proposed zeta converter in terms of (a) real power and (b) reactive power.

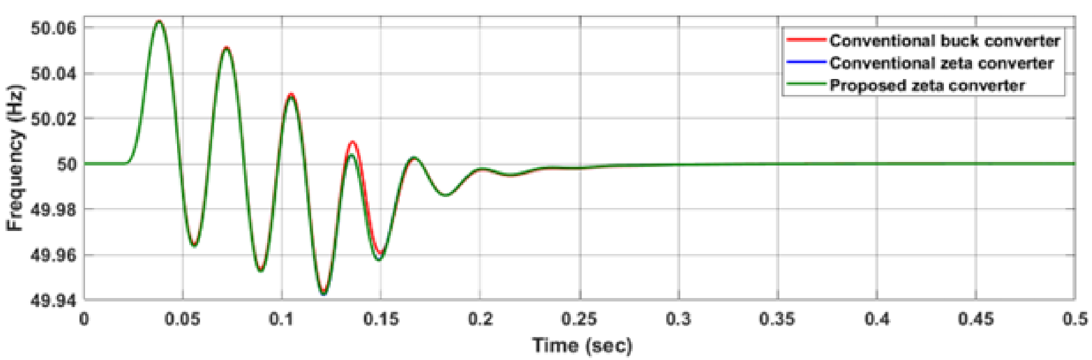


Figure 8. Frequency of conventional buck converter, conventional zeta converter, and proposed zeta converter.

3.3. Power factor and Efficiency

This research underscores the potential of the proposed closed-loop battery current-controlled zeta converter to enhance power factor and efficiency in EV charging stations. The simulation was conducted for 0.5 seconds, capturing the power factor on the grid side for both the conventional and proposed converters as illustrated in Figure 9. The conventional converter exhibited a power factor of 0.8. However, a notable improvement to 0.96 was achieved by the proposed charging station. Correspondingly, Figure 10 represents the efficiency of these converters during the same simulation period. The efficiency of the converter is calculated as given in Equation (19).

$$\text{Efficiency}(\%) = \frac{P_{out}}{P_{in}} \times 100 \tag{19}$$

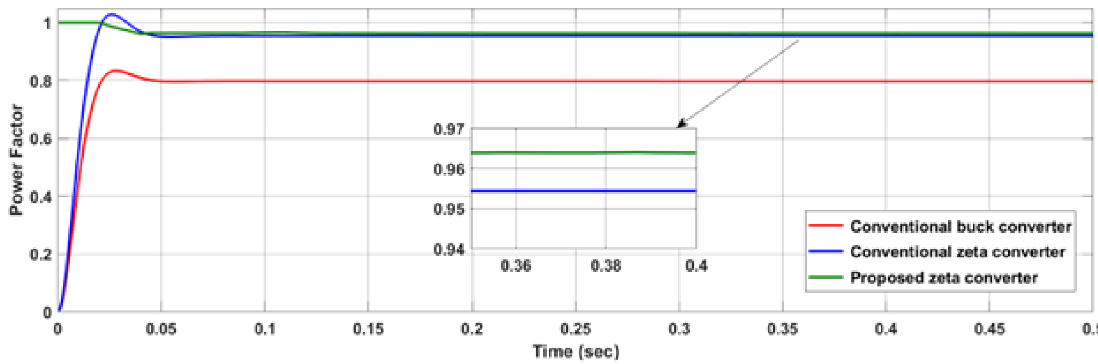


Figure 9. Power factors of conventional buck converter, conventional zeta converter, and proposed zeta converter.

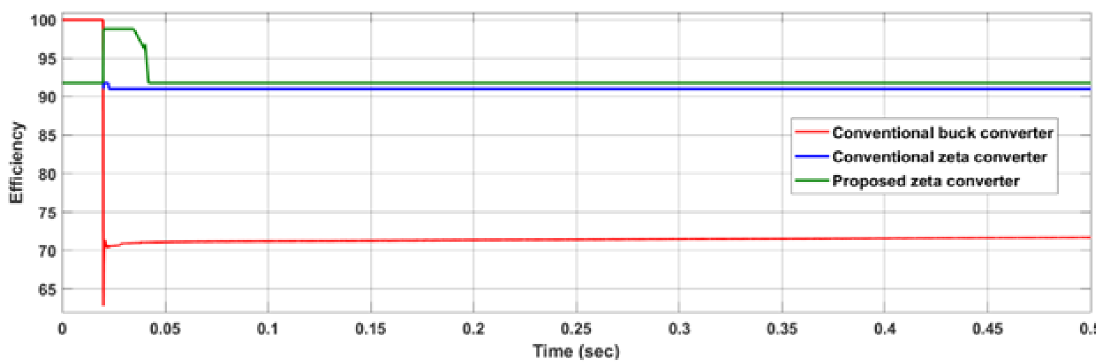


Figure 10. Efficiency of conventional buck converter, conventional zeta converter, and proposed zeta converter.

The results indicate that the proposed zeta converter operates with an efficiency of 91.8%, whereas the buck converter achieves an efficiency of 72.2%. This transition to the zeta converter configuration correlates with a reduction in system losses, leading to an overall improvement in converter efficiency.

3.4. Battery Characteristics

For modelling and simulation, the EV battery specifications are considered and listed in Table 2. The battery characteristic when the initial SOC of the battery is set at 20% is shown in Figure 11. As observed, the battery current is shown in a negative direction representing the charging of the battery through the converter.

Table 2. Performance comparison of conventional and proposed systems.

Battery Specifications	Parameter Values
Battery Type	Lithium-ion
Nominal Voltage	60V
Rated Capacity	14Ah
Internal Resistance	42.857mΩ
Charge Current	2A
SoC	20%
Maximum Charge Voltage	69.84V
Charging temperature range	0°C-45°C

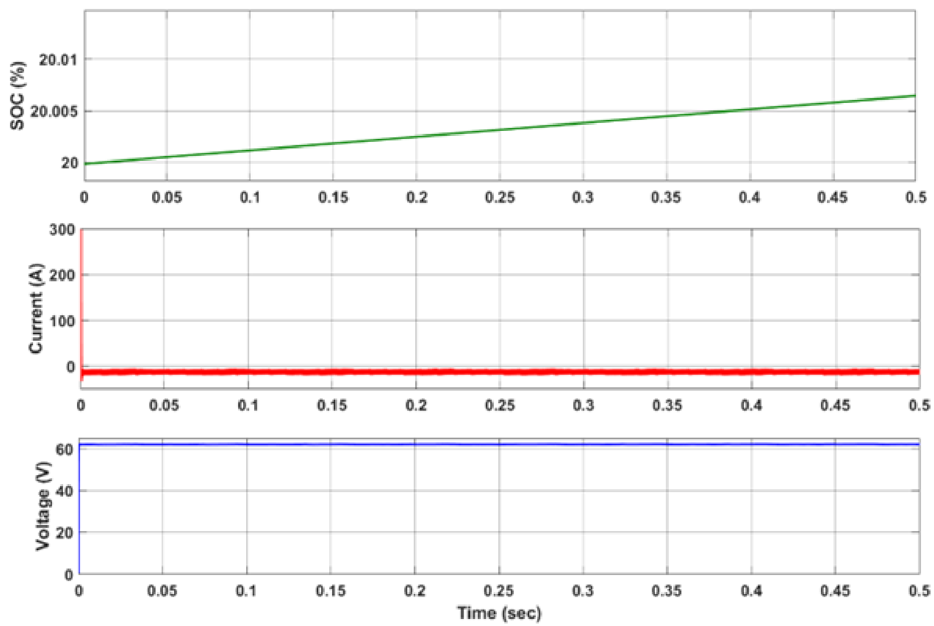
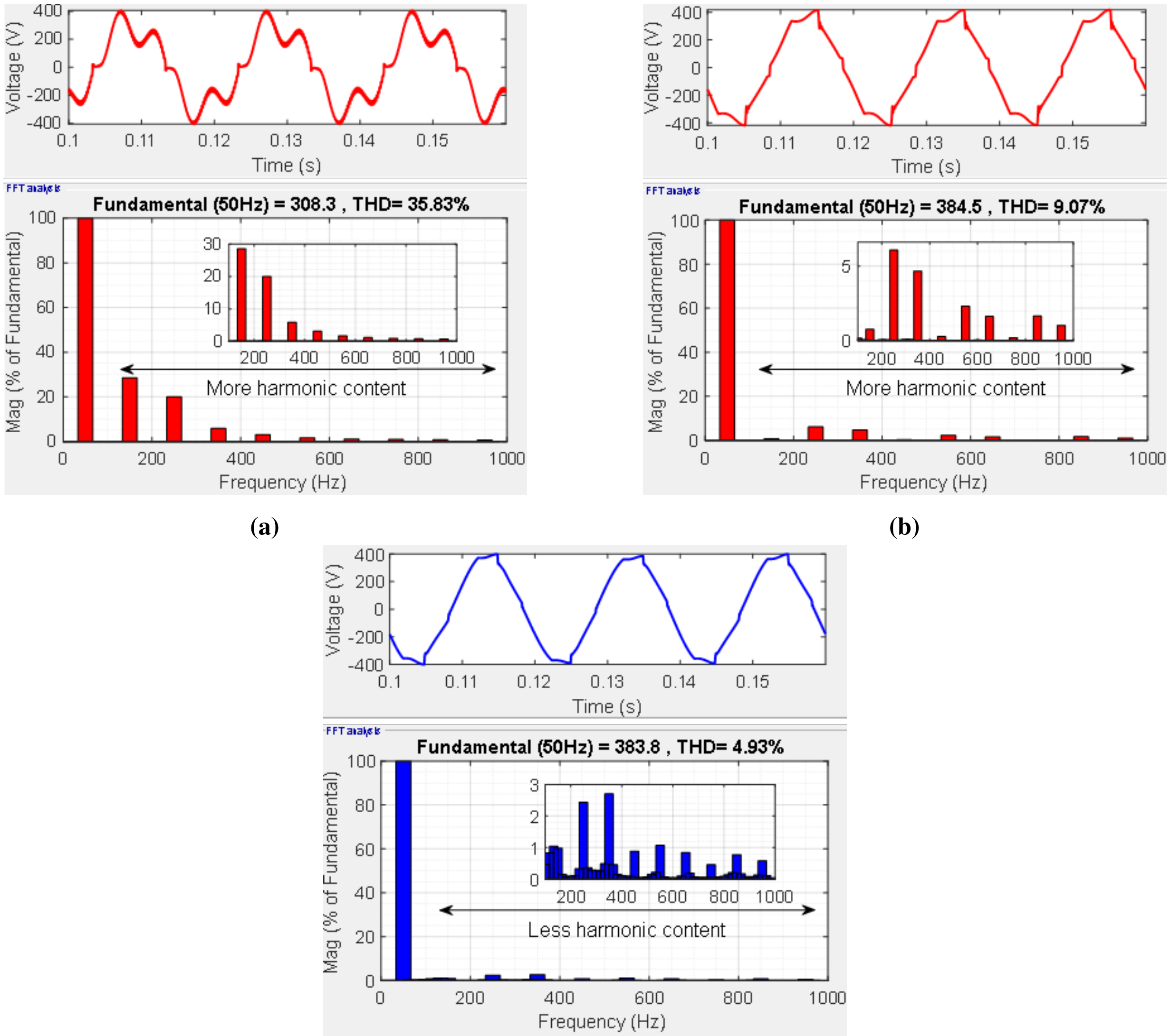


Figure 11. EV battery characteristics.

3.5. THD Analysis

The analysis is carried out on the grid side voltage and current to observe the THD produced with conventional and proposed systems. THD of grid voltage is plotted as shown in Figure 12 and THD of the grid currents is plotted as shown in Figure 13. The summary of the quantitative THD values obtained for voltage and current characteristics is given as follows.

- The voltage THD of the AC bus, when the charging stations are designed with conventional buck converter and conventional zeta converter, are measured as 35.83% and 9.07% respectively. While, with the proposed closed-loop battery current-controlled zeta converter charging station, the voltage THD is greatly reduced to 4.93%, which adheres to the permissible limit of 5% that is defined by IEEE 519.
- Similarly, the current THD of AC bus when the charging stations are designed with conventional buck converter and conventional zeta converter, are measured as 41.81% and 12.70% respectively. While, with the proposed closed-loop battery current-controlled zeta converter charging station, the current THD is greatly reduced to 1.90%, which adheres to the permissible limit of 8% that is defined by IEEE 519 standard.



(a) **(b)**

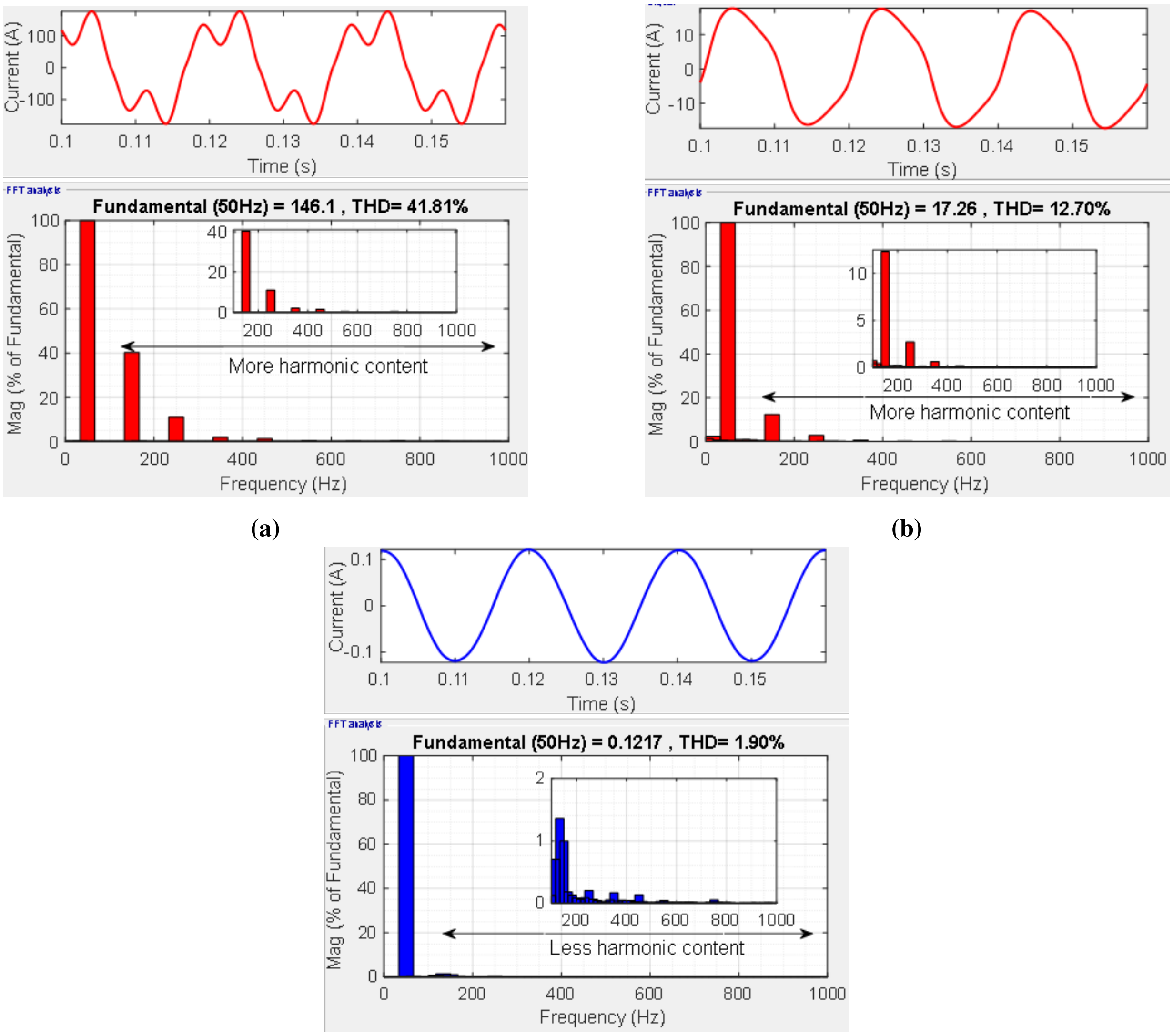
(c)

Figure 12. AC bus voltage THD obtained with (a) conventional buck converter, (b) conventional zeta converter, and (c) proposed zeta converter.

From these results, it is observed that there is a significant improvement in THD with the proposed charging station when compared to conventional methods.

3.6. Summary and Discussion of Results

The comparisons are made with respect to various power quality parameters, such as voltage THD, current THD, power factor, and efficiency. The system's overall power factor improved by 0.16, efficiency improved by 19.6%, voltage THD reduced by 30.9%, and current THD reduced by 39.91%. From the results, it can be clearly understood that the voltage and current waveform quality have been significantly improved from the conventional to the proposed scheme, and an overall improvement in converter efficiency. The effectiveness of the proposed scheme is evident from the measurable outcomes summarized in Table 3. Based on the quantitative analysis of all simulation results, it can be concluded that the performance of the proposed converter is superior to that of the conventional converters.



(a) **(b)**

(c)

Figure 13. AC bus current THD obtained with (a) conventional buck converter, (b) conventional zeta converter, and (c) proposed zeta converter.

Table 3. Performance comparison of conventional and proposed systems.

Performance Parameter	Conventional Buck Converter	Conventional Zeta Converter	Proposed Zeta Converter	Standard Recommended Value
Power factor	0.80	0.95	0.96	1
Efficiency (%)	72.2	91.0	91.8	100
THD of V (%)	35.83 (Violated)	9.07 (Violated)	4.93	$\leq$ 5% (IEEE 519 Std)
THD of I (%)	41.81 (Violated)	12.70 (Violated)	1.90	$\leq$ 8% (IEEE 519 Std)

4. Conclusions

Electric vehicles are the main reason for an eco-friendly environment and pollution-free transportation. The EV charging stations are essential for charging electric vehicle batteries. This article proposed the concept of a closed-loop battery current-controlled zeta converter to an EV charging station to enhance the power quality. Various power quality parameters such as voltage and current characteristics, active and reactive power characteristics, total harmonic distortion (THD), frequency characteristics, power factor, and efficiency are studied and measured for the proposed scheme. Based on the collective findings, the significant advantages of the proposed scheme can be succinctly summarized as follows:

- The AC bus current THD computed from the results is 41.81% with the conventional buck converter charging station and 12.70% with the conventional zeta converter charging station, which violates the IEEE 519 standard. However, it is notably reduced and adhered to the standard limit with the proposed closed-loop battery current-controlled zeta converter charging station, which recorded a current THD of 1.9%, which adheres to the permissible limit of IEEE 519 standard, i.e., $\leq$ 8%. The overall current THD of the system was reduced by 39.91% with the proposed zeta converter.
- The AC bus voltage THD computed from the results is 35.83% with the conventional buck converter charging station and 9.07% with the conventional zeta converter charging station, which violates the IEEE 519 standard. However, it is notably reduced and adhered to the standard limit with the proposed closed-loop battery current-controlled zeta converter charging station, which recorded a voltage THD of 4.93%, which adheres to the permissible limit of IEEE 519 standard, i.e., $\leq$ 5%. The overall voltage THD of the system was reduced by 30.9% with the proposed zeta converter.
- The power factor computed from the results is 0.80 with the conventional buck converter charging station and 0.95 with the conventional zeta converter charging station. While, in the proposed closed-loop battery current-controlled zeta converter charging station, it is slightly improved to 0.96. The overall power factor of the system improved by 0.16% with the proposed zeta converter.
- The efficiency computed from the results is 72.2% with the conventional buck converter charging station and 91% with the conventional zeta converter charging station. While, in the proposed closed-loop battery current-controlled zeta converter charging station, it is slightly improved to 91.8%. The overall efficiency of the system improved by 19.6% with the proposed zeta converter.

Thus, based on the results obtained from the proposed model, it is concluded that the proposed closed-loop battery current-controlled zeta converter charging station has successfully outperformed the conventional buck and zeta-based charging stations, thereby being recommended as a well-suited converter for EV applications.

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