SIMULATION AND ANALYSIS OF SINGLE PHASE BIDIRECTIONAL TOTEM POLE ON-BOARD CHARGER

By

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ABSTRACT

In the contemporary era, the global rise of two-wheeler electric vehicles has become pivotal for sustainable development and energy conservation. The necessity for an efficient and effective charger for these vehicles is evident. While numerous two-wheeler electric vehicle chargers are available in the market, this research paper introduces a novel on-board charger tailored specifically for two-wheeler vehicles. The proposed charger integrates totem pole AC-DC converter and DC-DC converter to achieve unity power factor and ensure constant current battery charging, thereby enhancing overall efficiency. The incorporation of these converters not only improves charging performance but also facilitates a higher degree of energy conservation. This paper delves into the simulation and analysis of this innovative two-wheeler electric vehicle charger. The use of both converters is instrumental in minimizing harmonics injected into the grid, contributing to enhanced grid compliance. The presented findings suggest that chargers of this nature are poised to gain popularity in future, addressing the growing demand for efficient and sustainable charging solutions for two wheeler electric vehicles.

Keywords: Electric Vehicle Charger, Totem Pole Converter, Isolated Full Bridge Converter, Simulation and Analysis, Constant Current Battery Charger.

INTRODUCTION

The current automotive trend emphasizes electric vehicles (EVs) to reduce emissions, featuring Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicle (BEVs) charged from the AC grid. To achieve extended electric range, larger battery packs demand higher-rated charger circuits. Chargers, either-off board resembling gas stations or on-board, face design constraints. Off-board chargers, free from volume restrictions, support several hundred kW charging power, yet encounter slower implementation due to high initial costs. The On-board chargers are resided within vehicles, overcome space issues but have volume limitations (Itoh et al., 2020).

The Off-board chargers show promise in popularizing BEVs, but slow implementation is expected due to high initial costs. The On-board chargers, integral for BEVs, resolve location issues but face volume restrictions as they are embedded in the engine compartment (Zhu et al., 2024).

Conventional single-phase charger circuits typically follow a two-stage configuration comprising an AC to DC rectifier stage and an isolated DC to DC stage (Kumar & Yi, 2022; Ramaiaha et al., 2018; Tang et al., 2016).

The bridgeless single-stage half-bridge AC to DC topology, as presented in (El Idrissi et al., 2022), is designed with semiconductor devices reduction. While it effectively minimizes the number of semiconductor components, its Discontinuous Conduction Mode (DCM) operation results in substantial input filter demands and increased conduction losses.

The isolated single-stage AC to DC topology, employing a matrix converter as outlined in (Gupta et al., 2023), is devised to minimize the DC link capacitor. Despite this advantage, the circuit requires bidirectional switching devices, hindering the reduction in the number of switches.

In electric vehicles, the vehicle charger employs high-frequency switching power supply technology to meet the demands of lightweight design, high power density and enhanced conversion efficiency. Two stage charger structures (Itoh et al., 2020; Kumar & Yi, 2022; Ramaiaha et al., 2018; Tang et al., 2016; Zhu et al., 2024), comprising an AC to DC converter and a DC to DC converter are prevalent due to their higher power factor, lower harmonic content and superior conversion efficiency compared to single-stage chargers. Although the two stage structure incurs higher costs, it is widely adopted in current on-board chargers.

The AC to DC converter in the front stage stabilizes the DC bus voltage, suppresses current harmonics and enhances power factor and utilization. In a specific design (Jacques et al., 2017), diode and boost circuits serve as the front-stage AC/DC converter, utilizing an average current control strategy for continuous current control.

Despite its advantages in simplicity and high power factor, this topology suffers from reduced system efficiency due to a high number of switching devices in the current flow path. Strategies to mitigate diode switching losses are discussed in (El Idrissi et al., 2022; Gupta et al., 2023), incorporating soft-switching techniques with added circuitry, complicating circuit control.

To address the challenge of reducing switching device count in the current flow path, researchers worldwide are exploring bridgeless PFC converter topologies. An innovative totem-pole bridgeless Boost PFC converter is introduced in (Dini et al., 2023; Gupta et al., 2020), characterized by minimal switching devices, reduced conduction losses compared to conventional bridgeless PFC designs, and an effective solution to common mode noise issues.

The two-stage systems offer a straightforward design with separate functional components but their drawback lies in increased size and cost due to a higher number of parts. Current research on on-board charger topologies explores advanced solutions integrating Power Factor Correction (PFC) and isolated DC/DC conversion into a single-stage setup for enhanced efficiency (Jacques et al., 2017). As outlined in this research paper, simulation and analysis have been conducted for a fast on-board charger. The promising outcomes of this model are poised to offer an enhanced solution for electric vehicle owners, particularly those utilizing two wheelers.

1. Modeling of Electric Vehicle Charger

The proposed model encompasses three primary elements: the grid, the on-board charger, and the Electric Vehicle (EV) battery. The charger is specified with the following ratings:

- Power: 1 kW
- Voltage: 230 V
- Frequency: 50 Hz

The electric vehicle under consideration is equipped with a 60V, 50 Ah/3kWh Li-ion battery. The intermediate capacitor and the battery charging current are regulated at 400 V and 16.67 A, respectively. The on-board charger features a circuit diagram, as illustrated in Figure 1.

In this EV charger, a totem pole converter is employed for AC to DC conversion, replacing the boost Power Factor Converter (PFC) due to its superior efficiency. The

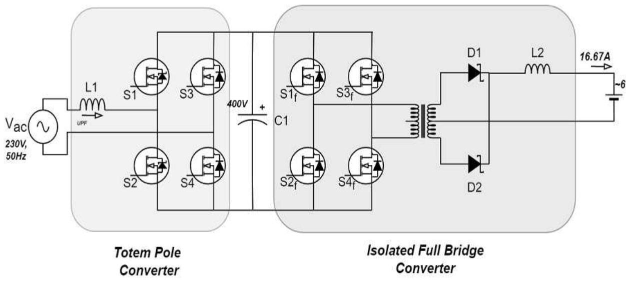


Figure 1. Circuit Diagram of Proposed on-board Charger

converter is rated at 400 V and 10 A. To ensure galvanic isolation between the battery and the grid, a full bridge converter is utilized, connected on the primary side of the transformer. The full bridge converter has a rating of 400 V and 6 A. In the secondary side, diodes D1 and D2 are connected, each with a rating of 150 V and 20 A.

The modern power supply designs demand sophisticated power factor correction circuitry to meet stringent power factor standards while ensuring high efficiency and cost-effectiveness. Although, interleaved boost PFC is the widely adopted topology, the emergence of wide-bandgap semiconductors has facilitated the adoption of bridgeless totem-pole PFC.

2. Working of Proposed on Board Charger

In this section, the working principle of the on-board charger has been discussed and shown in Figure 1. The initial phase of a totem-pole Power Factor Correction (PFC) converter is the rectification stage, where Alternating Current (AC) from the grid undergoes conversion into a pulsating Direct Current (DC). The diode rectifier plays a crucial role in achieving this pulsating DC. Subsequently, a capacitor is employed to alleviate this ripples present in the pulsating DC voltage, leading to the attainment of a stable and uninterrupted DC voltage.

The pulsating DC is then fed into a boost converter, which is responsible for boosting the voltage to the desired level. The boost converter increases the DC voltage to a level higher than the peak of the incoming AC voltage.

The unique aspect of the totem-pole PFC converter is the totem-pole configuration of MOSFETs in the next stage. The totem-pole arrangement involves using two transistor switches in a push-pull configuration-one on the high side and one on the low side. This configuration allows better efficiency and reduced switching losses.

The sophisticated control logic is employed to drive the totem-pole switches efficiently. This control logic ensures that the switches are turned ON and OFF at the right times to achieve power factor correction.

The output of the totem-pole PFC converter is then filtered and regulated to provide a stable high quality DC voltage. This DC voltage is used in the power electronic loads or is further processed for charging batteries in electric vehicles. The inductor helps to filter the current and smooth out variations in the output current. It helps to provide stable and well controlled output current.

A totem pole converter is a derived topology of a boost-PFC converter and it achieves higher efficiency compared to all the other boost-PFC derived topologies. The circuit diagram of totem pole converter is shown in Figure 2.

A totem pole converter consists of two legs: a high-frequency leg and a low-frequency leg. The high-frequency leg functions at the switching frequency and employs wide band gap devices, chosen for their faster switching times and lower switching energy. Conversely, the low-frequency leg operates at the power frequency and utilizes silicon-based diodes or MOSFETS to facilitate unidirectional or bi-directional power flow. In the model, the silicon carbide (SiC) and silicon (Si) based MOSFETs are specifically chosen for the high-frequency and low-frequency legs respectively. The controller successfully attains a unity power factor at the supply terminals while also ensuring that the intermediate capacitor voltage remains constant at a predetermined value.

The DC-DC converter employs an isolated full bridge topology, leveraging a double-ended design to enhance power capability. The key components include a square-wave inverter, a center-tapped transformer for improved efficiency and a diode rectifier utilizing Schottky diodes to minimize recovery losses. The Schottky diode offer several advantages that make it suitable for this kind of

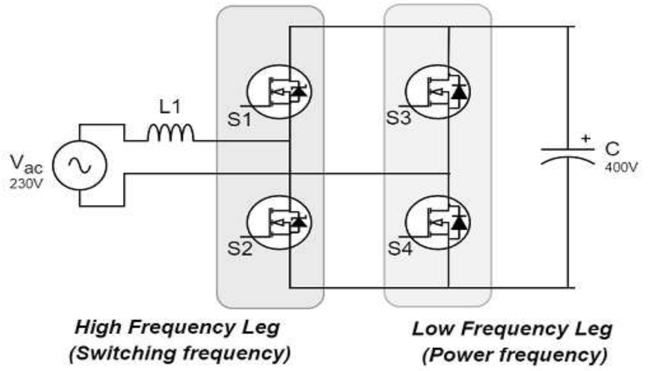


Figure 2. Circuit Diagram of Totem Pole Converter

applications:

- These diodes have a lower forward voltage drop compared to standard PN junction diodes. This lower voltage drop results in faster switching speed, which is crucial in totem pole chargers.
- These diodes have low forward voltage drop. Due to the low forward voltage drop, the Schottky diode reduces power losses and improves overall efficiency. It is essential in electric vehicle chargers where energy efficiency is a priority.
- The Schottky diodes tend to have better temperature performance compared to standard diodes, which is advantageous in environments where temperature variations are expected, such as in EV charging systems.
- The Schottky diodes have a very fast recovery time, which reduces the chances of reverse recovery-related issues like ringing or overshoot, making them more suitable for high-frequency switching applications.
- Schottky diodes are smaller and lighter compared to standard diodes with similar current ratings, which helps in reducing the overall size and weight of the charger system, an important consideration in electric vehicle applications.

Therefore, the fast switching speed, low forward voltage drop, temperature performance, fast recovery time and compact size make Schottky diodes well-suited for use in totem pole-based chargers for two wheeler electric vehicles, providing efficiency, reliability and compactness.

To emulate constant current mode in battery charging, the controller regulates the output current to a reference value. The circuit diagram of DC-DC converter is shown in Figure 3 Illustrates the circuit configuration of an isolated full bridge converter.

The isolated DC-DC converter can be represented using three different reliability levels for modelling i.e. the average fidelity, switching fidelity and averaged switching fidelity. But, in this research paper, the average fidelity is used.

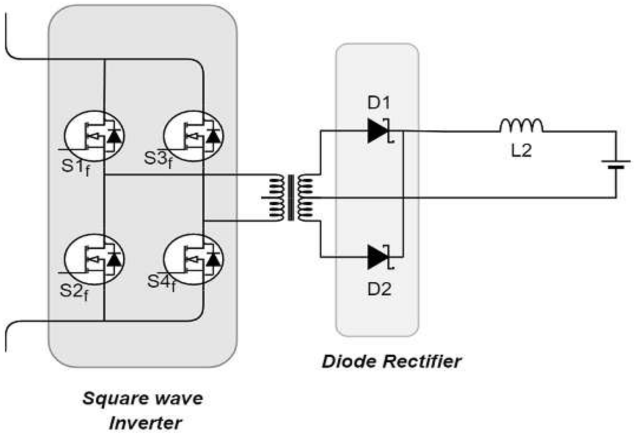
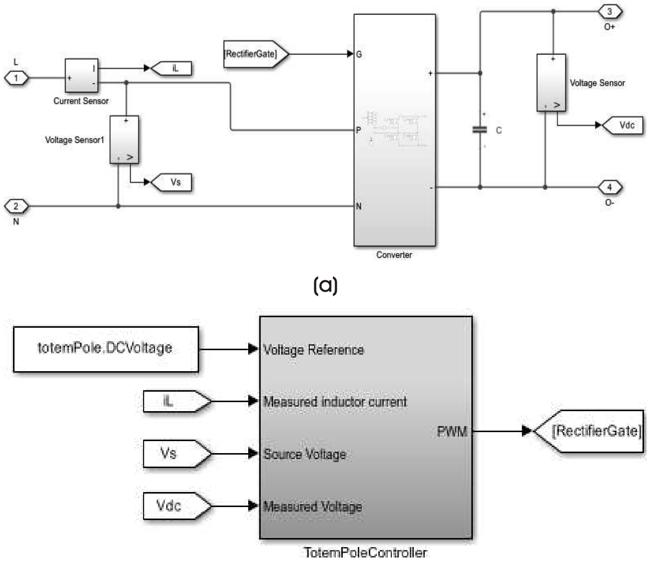


Figure 3. Circuit Diagram of DC-DC Converter

3. Simulation Model of Charger: Methodology and Implementation

The simulation model of proposed charger has been made in the MATLAB Simulink latest environment and shown in Figure 4 (a) and the controller in Figure 4(b). The devices parameters used in simulation is given in Table 1. The switching frequency is considered 33 kHz.

Since, the totem pole converter is the type of bidirectional DC-DC converter therefore both current and voltage sensors play crucial roles in monitoring and controlling the power flow. The current sensor has been employed to measure the electric current flowing through the converter. It provides feedback to the control system,



(a)

(b)

Figure 4. Simulation Models, (a) Totem Pole Converter Based Charger, (b) Totem Pole Controller

Device Name	Parameter Name	Values
N-Channel MOSFETS	Threshold Voltage	2.5 V
	OFF state conductance	$1\times10^{-5}\ \Omega^{-1}$
	Switching ON Loss	1×10^{-6} J
	Switching OFF Loss	1×10^{-6} J
	Drain Source Current	0 A
	Drain Source Voltage	0 V
	Junction Temperature	25 °C
Diodes	Reverse Recovery Loss	0 J
	Diode OFF conductance	$4\times10^{-5}\ \Omega^{-1}$
DC-DC Converter	Current Reference	16.667 A

Table 1. Devices Parameters used in Simulation

allowing it to regulate and maintain the desired current levels. In totem pole converter, which typically consists of upper and lower switches, the current sensor helps in implementing control strategies such as current-mode control. This ensures precise regulation of the output current, making it suitable for applications like battery charging or power transfer.

The voltage sensor is responsible for measuring the voltage across certain components in the converter circuit. This information is vital for the control system to maintain proper voltage levels at different points in the circuit. In a totem pole converter, voltage sensors are often used to monitor the input and output voltages. This data aids in implementing voltage control strategies and ensures that the converter operates within the desired voltage range. Voltage sensors contribute to the overall stability and efficiency of the converter by providing feedback for closed loop control. The complete theory of Totem pole converter based charger has been explained through Figures 1-3. The simulation model of the totem pole controller is illustrated in Figure 4(b). The controller incorporates four control parameters on the input side, namely the totem pole DC voltage serving as a voltage reference, the measured input current, the source voltage and the measured output voltage. Pulse Width Modulation (PWM) is employed to enable precise control of power flow, facilitating voltage regulation, current limiting and efficient operation within the power supply system. The primary function of PWM is to shape the output waveform in a controlled manner, ensuring the attainment of desired characteristics.

The output of the controller is directed to the Rectifier Gate, which is applied on the input side of the converter, as depicted in Figure 4(b). This configuration allows the totem pole controller to govern the power flow and regulate key parameters, contributing to the overall effectiveness and stability of the power supply system. The controller accomplishes a unity power factor at the supply terminals while also ensuring the intermediate capacitor voltage remains consistently at a predetermined set value. The Totem pole converter is a specific topology derived from the boost Power Factor Correction (PFC) converter. It stands out for its superior performance when compared to other topologies derived from the boost PFC configuration. This design modification enhances the overall performance and efficiency of the converter, making it a favorable choice in applications where energy efficiency is a critical factor.

The isolated DC-DC converter can be represented using three different fidelity levels in its modelling. The simulation model can be made for three fidelity levels i.e. average converter, average switching converter and switching converter but in this research paper average fidelity has been chosen for its better performance. The simulation model of average fidelity is shown in Figure 5. During transient conditions, utilizing average fidelity is beneficial due to its faster simulation times. This option is set as the default in the MATLAB simulation. The simulation model for average fidelity is shown in Figure 5.

Averaged fidelity switching is commonly employed for verifying the converter's operation. This variation utilizes averaged switching for quicker simulation times.

The EV battery pack is represented by modelling the battery cells arranged in series and parallel configurations, along with sensors to measure the battery

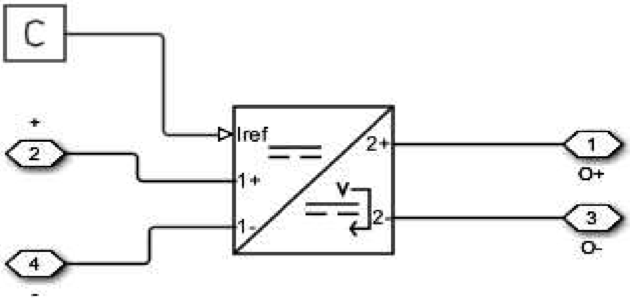


Figure 5. Simulation Model of Average Fidelity

terminal voltage and output current. The individual cell of the battery pack is simulated using the Table-based battery available in the Simulink library. This block is configured with the pre-parameterization for the Panasonic NCRBD18650, which has a rating of 3.6 V and 3.03 Ah. The arrangement of the batteries in the pack is designed to meet the specified voltage and ampere-hour requirements. The simulation model is shown in Figure 6.

In the simulation model, the vector of State of Charge (SOC) is given in Table 2. Table 2 represents vector of SOC values, SOC is a measure used to express the current capacity of a battery relative to its maximum capacity. It is often represented as a percentage ranging from 0% (fully discharged) to 100 % (fully charged).

The Cell Capacity is 3.153 hrA. The discharger cycle vector is given in Table 3. Table 3 represents a vector of discharger cycle values. Discharger cycle refers to the number of cycles a battery undergoes during discharging processes. A cycle typically involves discharging the battery from a certain state of charger to another, followed by recharging it back to its initial state.

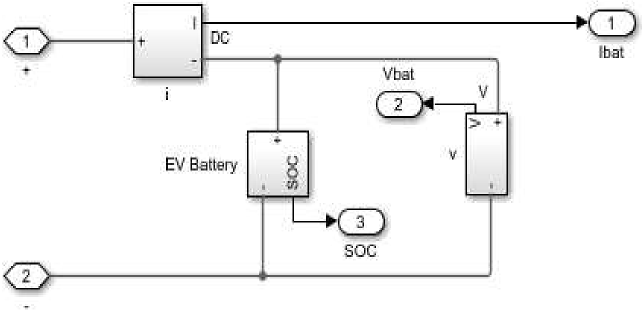


Figure 6. Simulation Model of EV Battery Pack Authors and Affiliations

Vector of SOC Values	[0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.1 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18 0.19 0.2 0.21 0.22 0.23 0.24 0.25 0.26 0.27 0.28 0.29 0.3 0.31 0.32 0.33 0.34 0.35 0.36 0.37 0.38 0.39 0.4 0.41 0.42 0.43 0.44 0.45 0.46 0.47 0.48 0.49 0.5 0.51 0.52 0.53 0.54 0.55 0.56 0.57 0.58 0.59 0.6 0.61 0.62 0.63 0.64 0.65 0.66 0.67 0.68 0.69 0.7 0.71 0.72 0.73 0.74 0.75 0.76 0.77 0.78 0.79 0.8 0.81 0.82 0.83 0.84 0.85 0.86 0.87 0.88 0.89 0.9 0.91 0.92 0.93 0.94 0.95 0.96 0.97 0.98 0.99 1]

Table 2. Vector of SOC Values

Vector of Discharger Cycle	[1 5 9 13 17 21 25 29 33 37 41 45 49 53 57 61 65 69 73 77 81 85 89 93 97 101 105 109 113 117 121 125 129 133 137 141 145 149 153 157 161 165 169 173 177 181 185 189 193 197 201 205 209 213 217 221 225 229 233 237 241 245 249 253 257 261 265 269 273 277 281 285 289 293 297 301 305 309 313 317]

Table 3. Vector of Discharger Cycle

4. Analysis of Results: Insights and Findings

Figure 7 illustrates various parameters of totem pole converter with average fidelity based charger for ideal switching. The key observations are as follows:

The voltage across the capacitor stabilizes at 400 V and shown in Figure 7(a), indicating a consistent and settled state. The stability of the capacitor voltage at 400 V reflects a robust equilibrium within the systems. This consistent voltage level suggests that the capacitor has reached a steady start, demonstrating its ability to store and release electrical energy in a controlled manner. Such stability is pivotal for the reliable operation of the converter, ensuring intermediate energy storage remains within a desired voltage range. This observation instills confidence in the consistent and controlled functioning of the ideal switching totem pole converter.

The grid voltage and current have been shown in Figure 7(b), notably, the grid current demonstrates a synchronized phase with the grid voltage. The alignment suggests a well-coordinated relationship between the two components. This synchronous alignment between the grid current and grid voltage signifies a harmonious interplay within the power conversion system. The correlation in phase between these two essential parameters is indicative of a well-coordinated and efficient interaction. This coordinated relationship is crucial for optimal power transfer and utilization within the converter.

The synchronized phase relationship between the grid current and voltage points to seamless exchange of electrical energy between the converter and the grid. Such coherence is essential for minimizing power losses and ensuring that the converter operates in concert with the grid's alternating current ability to adapt and respond to the dynamic nature of the grid, contributing to a stable and effective power conversion process.

The waveform of battery terminal voltage is shown in

Figure 7(c), a battery terminal voltage of 58 V suggests that the battery is currently operating or being charged at that voltage level. In a totem pole converter, the charger's primary function is to regulate and control the charging process of the battery. The battery terminal voltage is an essential parameter as it indicates the potential difference at the terminals of the battery. The specific voltage level is significant because it provides information about the charging state, health and capacity of the battery.

The waveform of battery charging current is shown in Figure 7(d), the charging current for the battery remains constant at a rate of 16.67 A. This stability in charging highlights a reliable and steady flow of current for the charging process. It indicates the reliability and efficiency of the charging process. This unwavering current flow is indicative of a well-designed charging mechanism within the converter, ensuring a stable and controlled replenishment of the battery.

The constancy of charging current is particularly significant for the longevity and performance of the battery. A steady flow of current prevents abrupt fluctuations that could potentially stress the battery cells, leading to wear and reduced overall lifespan. The reliable charging current observed in the plot points to a thoughtful design that priorities the health and sustained functionality of the battery.

The waveform of battery state of charge is shown in Figure 7(e). A battery State of Charge (SOC) of 0.100008 corresponds to a battery that is 10.0008% charged. It indicates that a relatively low charge level and the battery have a significant portion of its capacity available for use of further charging. SOC is a measure of the remaining capacity in a battery relative to its full capacity when fully charged. The value of 0 and 1 is often used to represent the SOC, where 0 indicates an empty or fully discharged battery and 1 represents a fully charged battery.

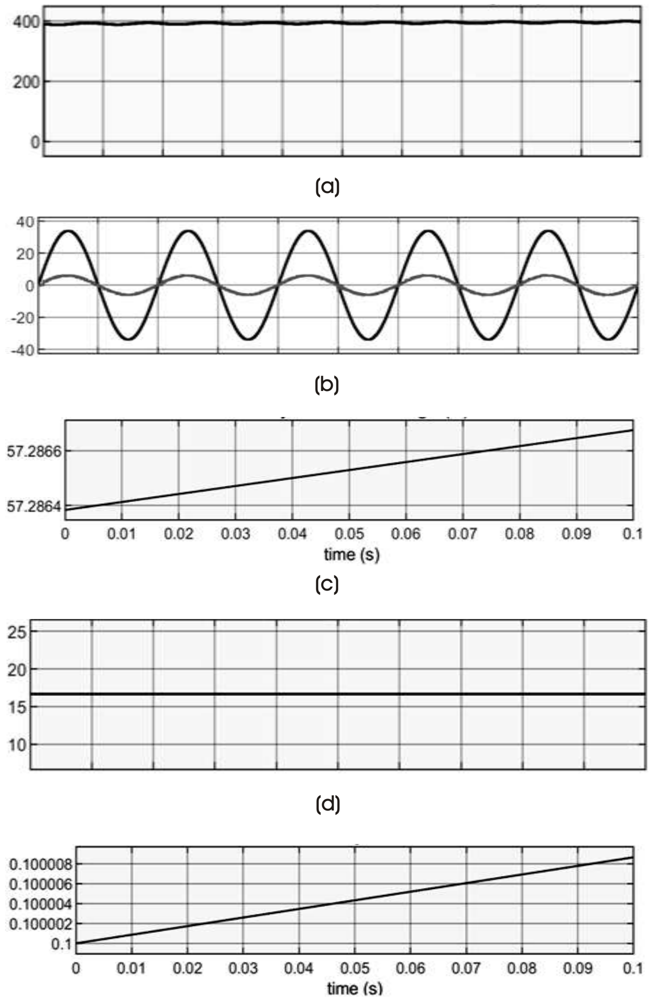


Figure 7. Parameters for Ideal Switching of the Totem Pole Converter for Average DC-DC Converter, (a) Capacitor Voltage, (b) Grid Voltage and Current, (c) Battery Terminal Voltage, (d) Battery Charging Current, (e) Battery State of Charging

Sl.No.	Parameters of Totem Pole Converter	
1	Capacitor Voltage or DC bus voltage	400 V
2	Battery terminal voltage	57.2867 V
3	Battery charging current	16.6667 A
4	Battery State of charging	0.100008

Table 4. Parameters of Totem Pole Converter

Table 4 presents results for various parameters of the totem-pole converter. Under ideal switching conditions, the DC bus voltage obtained 400 V, the battery terminal voltage is 57.2867 V, battery charging current is 16.6667 A. The battery state of charging, represented as a fraction or percentage, is theoretically estimated to be 0.100008 under ideal switching conditions. Hence, Table 1 provides clear theoretical values for key parameters of totem-pole converter. It clearly highlights the converter's performance under real-world conditions.

Conclusion

The automotive industry's shifts towards EVs are understood by the adoption of Plug-in Hybrid Electric Vehicles to mitigate emissions. However, the transition faces challenges particularly in charger designs. Off-board chargers akin to gas stations, promise rapid charging capabilities but are hindered by high initial costs, while on-board chargers integrated within vehicles confront volume limitations. Conventional charger circuits typically adopt a two-stage configuration for efficiency, although they come with increased size and cost.

Innovative topologies, such as the bridgeless PFC converter and totem-pole bridgeless Boost PFC converter, offer potential solution by reducing switching device count and conduction losses. Research also explores integrating PFC and isolated DC/DC conversion into a single-stage setup to enhance efficiency and reduce size and cost.

Therefore, in this research paper, a totem-pole bridgeless Boost PFC converter based charger has been modeled and obtained encouraging results. Simulation and analysis of on-board charger models demonstrate promising outcomes, offering enhanced solutions for EV owners, particularly in the realm of two wheelers. As the EV market continues to evolve, addressing charger design challenges will be crucial for widespread adoption, promoting sustainability and reducing environmental impact in the automotive sector.

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