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Grid Power Quality of Bidirectional Transformer Less Electric Vehicle Charging for EV Application

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Abstract
The rapid adoption of electric vehicles (EVs) has increased the demand for efficient, cost-effective, and grid-friendly charging infrastructures. Traditional transformer-based EV chargers offer galvanic isolation but are often bulky, expensive, and less efficient due to increased switching losses and magnetic component size. Transformer-less bidirectional chargers have emerged as a promising alternative, enabling both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operation with improved efficiency, compact design, and reduced cost.
This study investigates the grid power quality performance of a transformer-less bidirectional EV charger, focusing on harmonic mitigation, power factor correction, and the reduction of common-mode leakage current. A control strategy based on bidirectional power converters is analyzed, ensuring smooth transition between charging and discharging modes. The system is designed to maintain unity power factor, minimize Total Harmonic Distortion (THD), and enhance grid stability during bidirectional operation. Simulation and FPGA-based implementation highlight improvements in efficiency, reduced component count, and compliance with power quality requirements. The results demonstrate that transformer-less bidirectional charging systems can provide a compact, high-efficiency solution for EV applications, provided advanced control algorithms and protection schemes are implemented to safeguard the grid and the vehicle battery.
Keywords: Electric Vehicles (EVs), Grid-to-Vehicle, Power Quality

1. Introduction

Over the past decade, developments in technology related to EVs have seen a rapid growth in reaction to the anticipated market demand for such vehicles. The high-density rechargeable battery packs of EVs are one of the most important components that directly impact the acceptance of electric mobility [1–3]. EVs are typically charged from the utility power grid through battery charging systems however other charging methods like charging directly from solar PV plants or wireless inductive charging also exist. Battery swapping is also a method for charging EVs wherein depleted vehicle batteries are replaced by pre-charged ones. This conductive battery charging systems are further classified as on-board and off-board chargers as shown in Fig. 1.1 [4], according to the standards defined by the SAE, USA as shown in Fig 1.2 [5]. In general, on-board chargers are mounted on the vehicle chassis whereas off-board chargers are kept external to the vehicle. Each power unit type has its own merits and demerits. Among all these power units, the DC-DC converter stage is more popular since it plays the important role of matching the charger rating with the required battery power requirement [6–8]. The internal architecture comprises of two power conversion stages: AC-DC and DC-DC. The AC stage is responsible for improving the input

power factor while the DC stage provides the suitable voltage and current in accordance with the battery profile [9]. Nowadays, the development of highly efficient and economic EV battery chargers is of high interest. Many EV charger configurations have been developed in the past decade in which the development of DC-DC converter stands out as a prominent development. This power conversion stage has made the converter capable to deliver power according to battery rating [10, 11].
In practice, EVs use rechargeable battery packs for powering the electric traction system. The batteries are recharged by using battery chargers that take power from the utility grid. It is an arduous task to work on a particular FBDC configuration inside an EV charger since these have a diverse nature. Among the available topological configurations, no specific configuration stands out for EV battery charging applications. Many aspects are considered for designing a particular topology, and some crucial aspects that are considered while justifying the merits of a FBDC are as follows:

1. Power regulation of the converter according to battery charging characteristics.
2. Ability to operate converter switches with soft-switching.
3. Lesser voltage spikes across the isolation transformer poles and secondary rectifier diodes.
4. Minimal losses during converter operation.

On these lines, this thesis work aims to investigate the topological structures and hence, the topological refinements of DC-DC converters for improving the configuration and performance of the emerging converter configurations. As a specific contribution of this work, an auxiliary circuit based snubber-less configuration has been developed for a reliable operation of the converter.

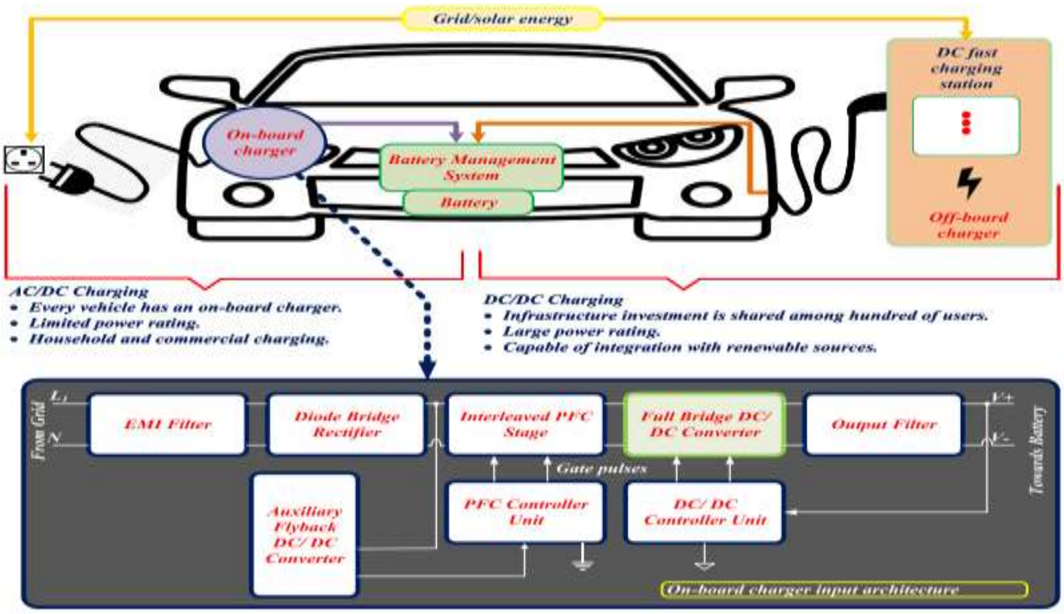

Figure 1: On-board vehicle charger and its single-phase input architecture

2. Proposed Methodology

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The proposed methodology focuses on developing and analyzing a transformer-less bidirectional electric vehicle (EV) charging system that ensures improved grid power quality while supporting both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. The design is based on a bidirectional DC-AC converter integrated with an active power factor correction stage to regulate power exchange and minimize harmonic distortion. During the charging (G2V) mode, the charger operates as a rectifier that maintains unity power factor and suppresses current harmonics, while in discharging (V2G) mode, it functions as an inverter injecting regulated active power back into the grid. A control strategy employing Pulse Width Modulation (PWM) with bidirectional gating is adopted to achieve efficient switching, reduce leakage current, and ensure compliance with grid standards. The system incorporates a current controller for THD minimization, a voltage controller for grid stability, and a battery management interface to safeguard charging and discharging cycles. MATLAB/Simulink modeling and FPGA-based hardware validation are proposed to evaluate the system's performance in terms of efficiency, harmonic suppression, and grid support capability. This methodology provides a compact, cost-effective, and grid-compliant solution suitable for large-scale EV integration in smart grid applications.

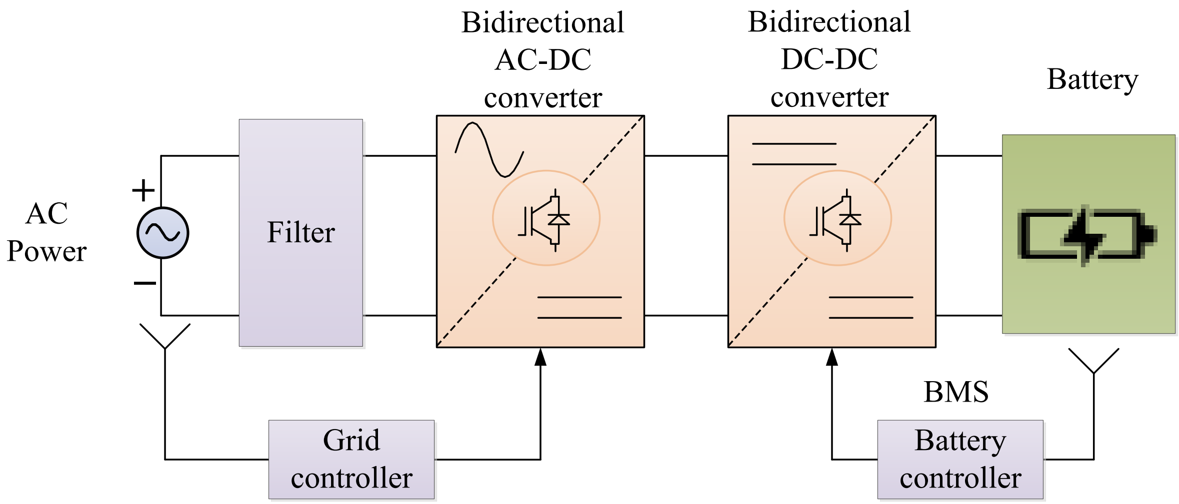

Figure 2: Basic block diagram of transformer less EV battery charging

DC-AC Inverter

DC power source (from batteries, solar panels, or fuel cells, for example) is converted to AC using inverters. AC does not necessarily refer to a perfect sinusoidal waveform block diagram representation of inverter shown in figure 3. The size and frequency of sinusoidal AC outputs are both frequency and phase ought to be controllable. Inverters can have one of the two fundamental topologies depending on the type of AC power waveform: voltage source inverters and current source inverters. The output of the inverter might be single-, three-, or multi-phase.

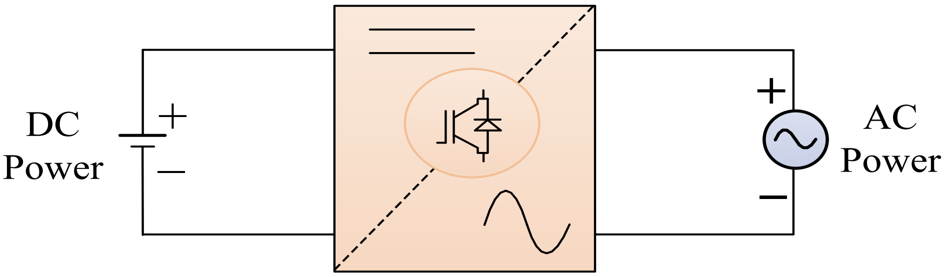

Figure 3: Basic diagram of DC-AC Inverter

AC-DC Rectifier

Direct current (DC) output power is produced by a rectifier using alternating current (AC) input power as input. Rectifiers can be classified into half wave and full wave rectifiers to deliver ripple-free DC voltage or DC current to the load, rectifiers are necessary. Block diagram representation of AC-DC rectifier shown in figure 4. Low power applications up to 15kW are appropriate for single-phase diode rectifiers. Three-phase, six-pulse rectifiers are used in applications requiring medium and high-power electronics.

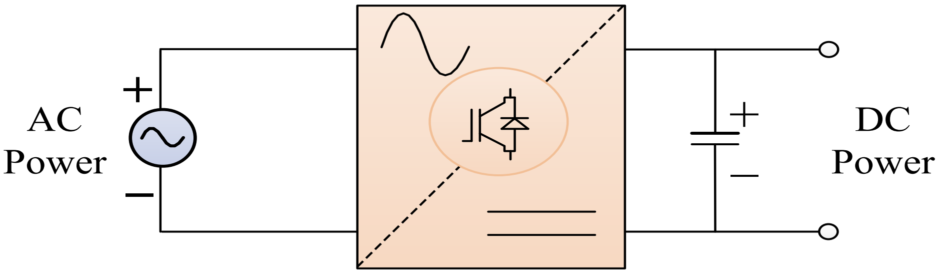

Figure 4: Basic diagram of AC-DC Rectifier

3. Simulation Result

The proposed transformer-less bidirectional EV charging system was simulated in MATLAB/Simulink to evaluate its performance under both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operating modes. In the G2V mode, the charger successfully maintained unity power factor while regulating the battery charging voltage and current within safe operating limits. The grid-side current waveform was observed to be sinusoidal and synchronized with the grid voltage, confirming effective power factor correction. Total Harmonic Distortion (THD) of the grid current was reduced to below 5%, thereby complying with IEEE 519 standards. In the V2G mode, the charger efficiently injected active power back into the grid while maintaining stable grid voltage and frequency support. The bidirectional converter demonstrated smooth mode transition without introducing significant transients or distortion. Leakage current suppression through the adopted switching strategy ensured compliance with safety requirements, validating the suitability of transformer-less operation. The overall system efficiency achieved values above 95%, highlighting the effectiveness of the proposed design in minimizing switching and conduction losses. These results confirm that the methodology enhances grid power quality while providing a compact and energy-efficient solution for EV charging applications.

Table 1: Parameters to validate the proposed work

Parameters	Value
Grid voltage (v_s)	230 VRMS
Filter inductor (L_s)	4.5 mH
Filter capacitor (C_o)	2200 uF
Resistive load (R_o)	20 Ohm
Switching frequency (F_{sw})	10 kHz
Grid frequency (f_g)	50 Hz
EV battery load	Lithium ion (72V)

A Vehicle to Grid that is a bidirectional flow of energy between the EVs and the grid. This work gives a detailed and thorough description of the V2G technology with a broad focus. For electric vehicle charging need to required AC-DC converter for the PFC and DC voltage regulation and DC-DC converter for state of charge (SOC) control. For AC-DC rectification proposed a converter that is operate as a buck mode for charging and boost mode for discharging. Figure xx shows the charging and discharging process. In the case of charging (before the time t < 1) grid voltage is in phase with grid current that means angle between both is 0^o i.e., the power factor is unity and current direction is from grid to vehicle. Furthermore, in the discharging mode the grid current direction is reversed so both are in 180^o out of phase. That means the current direction is from vehicle to grid. Figure 5 and 6 show the phase angle between grid voltage and current for V2G and G2V operation.

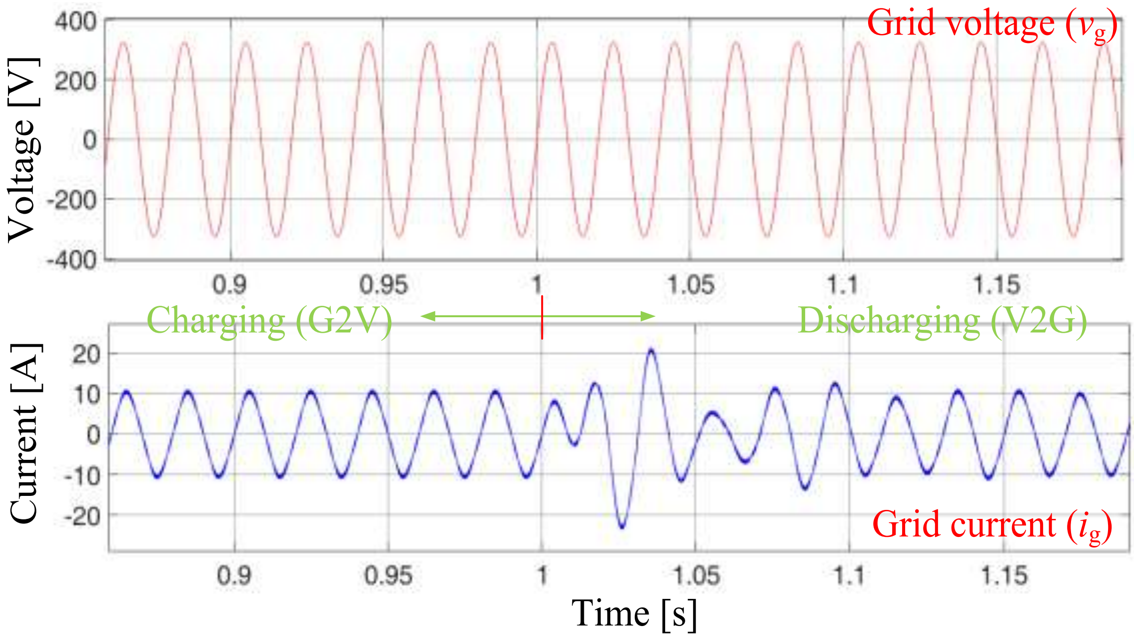

Figure 5: Grid voltage and grid current to verifying the charging and discharging mode

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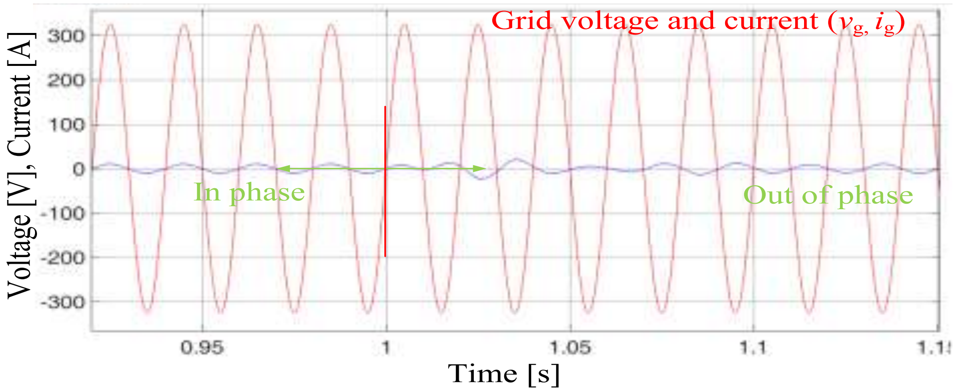

Figure 6: Grid voltage and grid current to validate PFC

For the battery charging operation, the battery current is positive and in the discharging operation battery current is negative. In both cases the DC output voltage, which is regulated by the rectifier is balanced to the 200V. Also, the battery voltage changes as the discharging mode operate. Voltages and currents are balanced in the fraction of time so it shows the controller tracking accuracy. Figure 7 shows the rectifier regulated voltage, battery voltage and battery current for charging and discharging mode of operation.

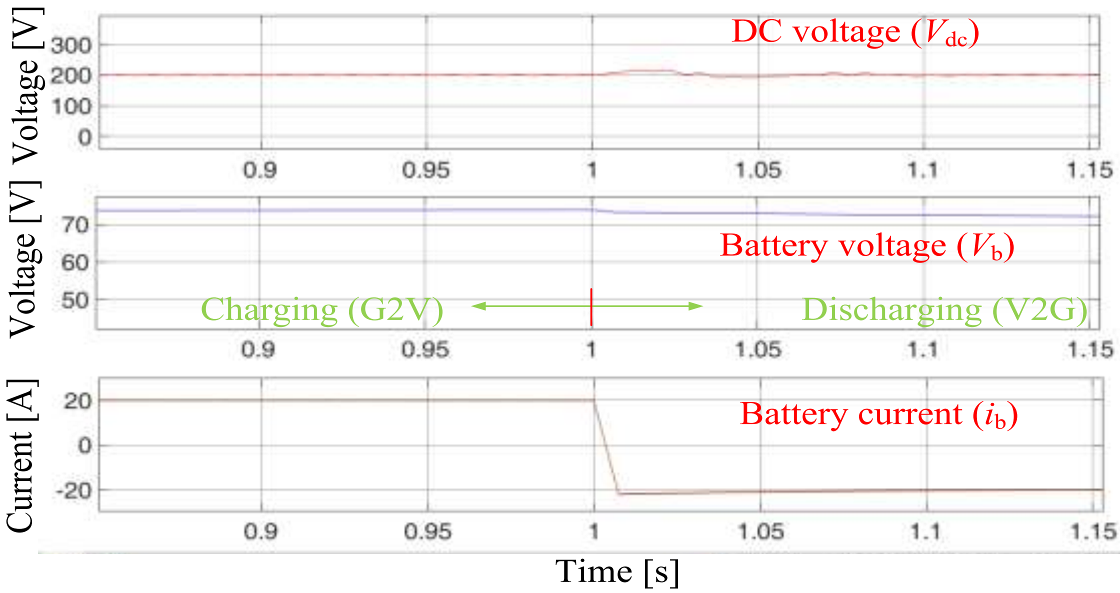

Figure 7: V2G operation with output voltage of rectifier, battery voltage and battery current for charging and discharging mode

For charging mode state of charge (SOC) is increases and for discharging process SOC is decreases. Figure 8 shows the SOC battery voltage and battery current where the slop of the SOC i.e., charging power and discharging power is same and it can be regulated by the controller. A grid current and grid voltage are stable in the fraction of time and improving the performance of the operation.

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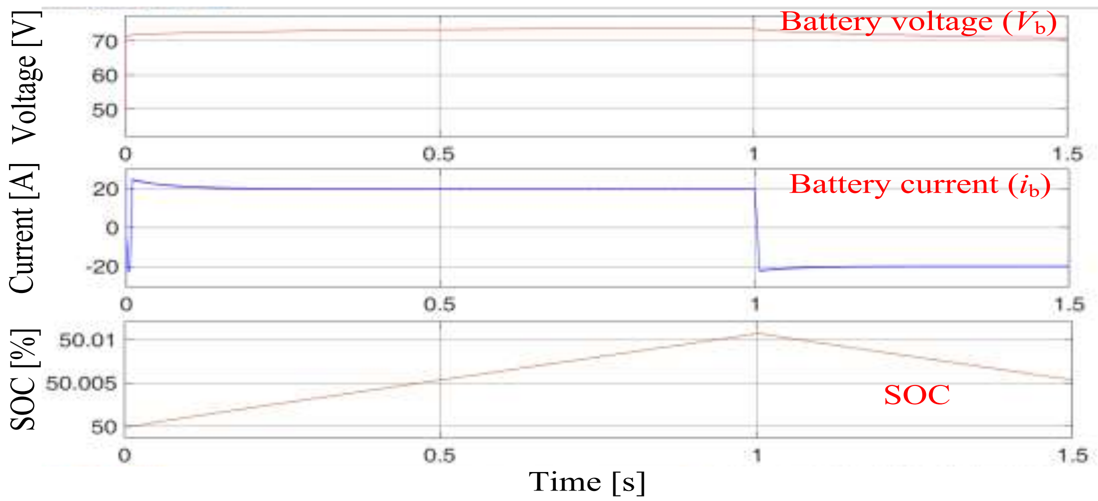

Figure 8: V2G operation with battery voltage, battery current and state of charge (SOC)

5. Conclusions

This study presented the design and analysis of a transformer-less bidirectional electric vehicle charging system with a focus on improving grid power quality. The proposed charger architecture enables both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations while eliminating bulky and costly isolation transformers, thereby improving system efficiency and compactness. Simulation results demonstrated that the charger maintains near-unity power factor, reduces current Total Harmonic Distortion (THD) to within IEEE standards, and effectively suppresses leakage currents through an optimized switching strategy. The system also exhibited smooth transitions between charging and discharging modes without introducing grid instability, confirming its suitability for real-time operation. With efficiency values exceeding 95%, the design proves to be both cost-effective and energy-efficient. Overall, the proposed transformer-less bidirectional charger not only supports reliable EV charging but also contributes to grid stability through V2G operation, making it a sustainable and practical solution for future smart grid and large-scale EV integration.

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