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Controller Design for Bridgeless Power Factor Correction and Dual Active Bridge Converters in Electric Vehicle Fast Charging Systems

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Electric vehicle charging, Bridgeless boost converter, Power factor correction (PFC), Grid-connected charger, Bidirectional DC-DC converter, Dual-active bridge (DAB), Fast charging, Vehicle-to-Grid (V2G), High efficiency, Power quality.

ABSTRACT

The proposed project outlines an advanced fast electric vehicle (EV) charging system that provides high efficiency in addition to being connected to the utility grid; it does this by eliminating the conventional AC/DC conversion stage of the diode bridge rectifier and replacing it with a new configuration called the Bridgeless (BL) Modified Boost Converter which has been enhanced by integrating power factor correction (PFC). The use of the PFC function in the proposed topology reduces the total amount of loss within the entire charging system due to reduced conduction loss as well as increased thermal performance due to reduced heat generation. In addition, the proposed topology also maintains a nearly unity power factor through the AC to DC conversion process performed by the BL-Modified Boost Converter and subsequently ensures compliance to all applicable power quality standards. A Bidirectional Dual Active Bridge (DAB) DC-DC Converter is then used to regulate and manage power flow between the EV battery and the PFC stage; the DAB has the added advantage of providing bidirectional functionality allowing for either the charging or discharging operation of the EV battery thus enabling Vehicle to Grid (V2G) capabilities. The use of modular design and the implementation of a new control strategy provide faster, more efficient, and smarter charging methods while reducing the amount of harmonic distortion present in the charging circuitry and increasing the stability of the grid. As such, this topology will be beneficial in supporting modern day EV charging infrastructure requirements which include energy efficiency, fast charging times, and grid compatibility.

1. INTRODUCTION

The widespread use of fossil fuel for electrical generation and heat produced by combustion engines continues to be a driving force behind the rapidly increasing air pollution and global warming issues. The transportation sector is a major consumer of fossil fuels and creates a massive source of pollution. Increased demand for higher amounts of electricity created by a growing population, ultimately leads to increased reliance on fossil fuels and further degradation of environmental quality. With the goal to address these problems, the Indian government initiated multiple strategies to minimize greenhouse gas emissions and achieve a goal of becoming a net-zero emission country by 2030. In pursuit of this vision, many new policies were implemented to support the transition of the transportation sector to electrical, including the creation of electrified rail systems and the ambitious goal of reaching 80 percent electric vehicle (EV) penetration among light vehicles by 2030 [1]. Although this vision offers great promise, there is still a barrier to realizing this vision – the availability of a sufficient amount of efficient, intelligent, and compliant EV charging infrastructure. Many of the existing EV charging devices do not meet international power quality standards such as IEC 61000-3-2 and IEEE 519 [2], [3] creating low power factor, high harmonic distortion, high energy loss and negative impact on grid stability.

As electric vehicles (EVs) are powered by rechargeable battery systems that require well-controlled charging circuitry to maximize longevity, safety, and performance, most commercial charging setups convert alternating current (AC) from the grid into direct current (DC) using a multi-stage power electronic interface. Most commonly, commercially available chargers employ a diode-bridge rectifier in the first stage of the interface [4], followed by isolated DC-DC converters such as flyback or forward converters to provide constant current (CC) and constant voltage (CV) during charging. Although these conventional interfaces have served well for many years, they have many limitations. For example, diode-bridge rectifiers create high input current distortion and lower the input power factor, and they require a lot of reactive power. Furthermore, due to high input voltages, the flyback topology becomes very inefficient and thermally stressed under high-power applications, and therefore, not suitable for fast and bi-directional charging. Modern power conversion strategies have been developed to remove the diode bridge and to improve power quality while providing bi-directional power flow and galvanic isolation. Of these strategies, the bridgeless boost (BL-Boost) topology has proven to be very effective front-end converter for power factor correction (PFC). The BL-Boost topology is able to reduce conduction loss by limiting the number of semiconductor components that conduct at the same time during each half-cycle. There are many published research articles that present various BL converter topologies based on dual boost configurations [5], [6], [7], [8], [9]. One of the primary advantages of these types of topologies is their improved thermal performance and simplified current shaping, both of which allow for more precise control of the charging process using digital techniques. Additionally, a single-loop digital PFC controller is used to maintain the phase relationship between the input current and the grid voltage, thus maintaining near unity power factor and low total harmonic distortion. Due to its ability to maintain these characteristics, the BL-Boost topology is very attractive for application in grid-connected EV charging systems. Therefore, numerous front-end BL boost topologies have been described for a wide variety of input voltage ranges [10], [11], [12], [13], [14], that must operate within the constraints of stringent electromagnetic compatibility and power quality regulations. After the PFC stage, a DC-DC converter is necessary to manage the charging of the batteries and to provide safety. The dual-active bridge (DAB) converter is a very promising candidate for this purpose. The DAB converter is comprised of two active full-bridge circuits that are coupled together via a high frequency transformer and a resonant inductor. The DAB converter regulates power flow between the grid and the battery using phase shift modulation and allows for bi-directional energy transfer. The DAB converter can operate efficiently over a wide variety of input and output conditions and supports soft-switching techniques such as zero-voltage switching that greatly reduces switching loss and improves efficiency [16], [17]. In addition to providing efficient operation, the DAB stage provides galvanic isolation and voltage scalability, thus enabling the charger to be compatible with a variety of battery chemistries and grid voltage levels. The combination of the BL-Boost converter and the DAB converter along with a high speed digital controller and sensor feedback mechanisms enables the creation of a smart, high-efficient, and grid-compliant EV charging system [18], [19]. The digital control unit continuously monitors input voltage, input current, output voltage, and battery state of charge to dynamically adjust the switching duty cycle and phase angle. This degree of control provides for smooth transitions between CC and CV modes, provides protection in case of abnormal operating conditions, and allows for smart features such as V2G operation, renewable energy integration, and real-time power quality monitoring. Therefore, a complete electric vehicle battery charging system was designed and simulated in the MATLAB/Simulink environment to assess the performance and efficiency of the proposed charging system. The proposed charging system employs a bridgeless boost PFC converter as the front-end stage and a dual-active bridge isolated DC-DC converter as the rear-stage converter [15]. Additionally, a closed-loop digital controller was employed to enable the proposed system to operate efficiently, accurately regulate the output voltage, and to satisfy power quality standards. The simulation results demonstrate that the proposed system exhibits low harmonic distortion, near-unity power factor, high efficiency, and reliable charging profiles under a variety of grid and load conditions. When compared to traditional flyback-based EV chargers, this approach demonstrates significant improvements in system performance, operational flexibility, and suitability for implementation into modern smart grid infrastructures.

2. SYSTEM CONFIGURATION

The widespread use of fossil fuel for electrical generation and heat produced by combustion engines continues to be a driving force behind the rapidly increasing air pollution and global warming issues. The transportation sector is a major consumer of fossil fuels and creates a massive source of pollution. Increased demand for higher amounts of electricity created by a growing population, ultimately leads to increased reliance on fossil fuels and further degradation of environmental quality. With the goal to address these problems, the Indian government initiated multiple strategies to minimize greenhouse gas emissions and achieve a goal of becoming a net-zero emission country by 2030. In pursuit of this vision, many new policies were implemented to support the transition of the transportation sector to electrical, including the creation of electrified rail systems and the ambitious goal of reaching 80 percent electric vehicle (EV) penetration among light vehicles by 2030 [1]. Although this vision offers great promise, there is still a barrier to realizing this vision – the availability of a sufficient amount of efficient, intelligent, and compliant EV charging infrastructure. Many of the existing EV charging devices do not meet international power quality standards such as IEC 61000-3-2 and IEEE 519 [2], [3] creating low power factor, high harmonic distortion, high energy loss and negative impact on grid stability.

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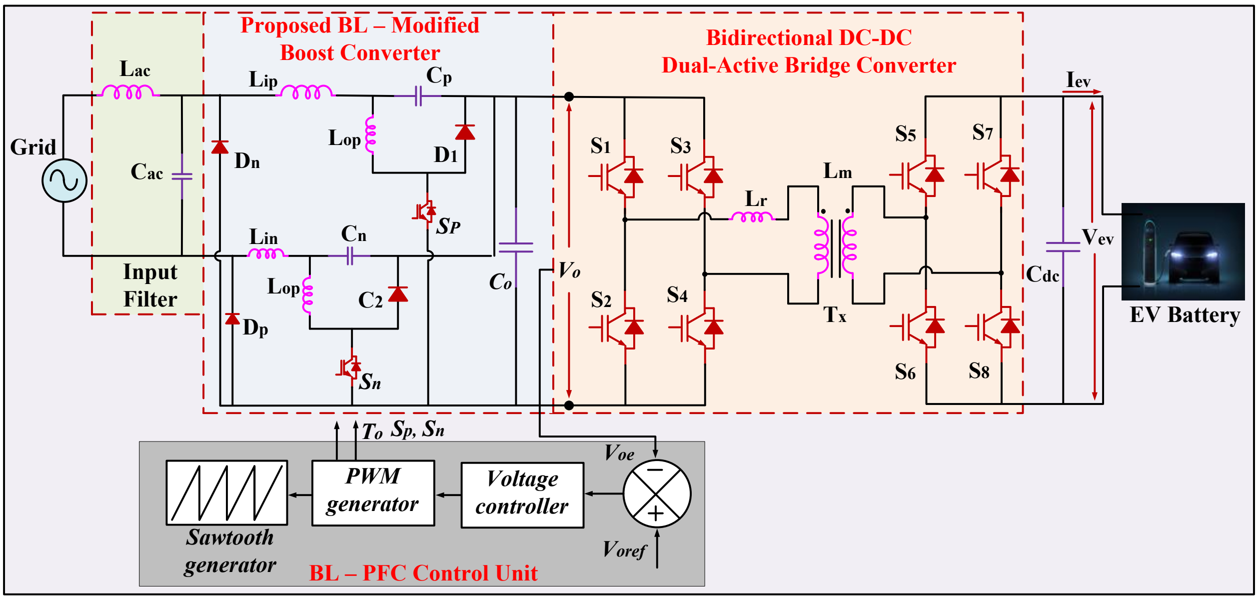


Fig.1 Proposed configuration for EV battery charging system

3. DESIGNING OF BL - PFC CONVERTER

The proposed BL EV Battery Charger has an enhanced input waveform designed for optimizing the EV battery charging process. The enhanced design allows the charger to charge the EV batteries efficiently at all times, while maintaining the desired CC/CV charging modes as a function of the battery SOC. Additionally, depending upon the type of charger application, the BL Converter will operate in CCM or DCM. As a result of increased battery costs in today's marketplace, the advantages of the DCM mode are significant, and in addition to helping minimize current stress on the battery, DCM mode minimizes the overall size of the converter and reduces the voltage stress on the converter components. For example, certain inductors have been optimized for DCM operation in order to enable a compact design of the charger. This not only provides better thermal performance but it also enables the development of a low-cost, high-performance charger.

A. Proposed Model

The novel bridgeless (BL) converter topology (as shown in Figure 2) has been developed to provide an optimized DC-link output for electric vehicle (EV) battery charging. A significant advantage of this new design is that it eliminates the need for a diode bridge rectifier (DBR). The DBR is one of the primary sources of harmonic distortion in the source side of the converter. Therefore, by eliminating the DBR, the THD performance of the entire converter can be greatly enhanced. Two parallel converter circuits have replaced the DBR and they are referred to as positive half-cycle converter and negative half-cycle converter. As indicated above, these converters are operated such that one converter is active during the positive half-cycle and inactive during the negative half-cycle; similarly, the other converter is active during the negative half-cycle and inactive during the positive half-cycle. The operation of the converters in such a manner results in reduced conduction losses, fewer simultaneously conducting components and increased system efficiency. In order to ensure that the converters maintain a unity power factor (UPF) and constant output voltage, each of them operates at a switching frequency of 20 kHz, with the positive half-cycle converter being active during the positive half-cycle and the negative half-cycle converter being active during the negative half-cycle. In addition, the input inductors (Lop and Lon) are designed to operate in Discontinuous Conduction Mode (DCM); this will minimize the size of the inductors and losses associated with their use as well as improve the thermal performance of the entire system. The output of the BL converter is connected to the EV battery via a Bidirectional DC-DC Dual Active Bridge (DAB) converter, which allows for efficient bidirectional power transfer and enables both charging and discharging operations. In addition, the DAB converter permits very accurate control over the different charging modes (i.e., CC and CV), which can be switched based on the SOC of the battery. Finally, a front-end input filter is used to eliminate higher order harmonics and to ensure that the input voltage and current remain in phase and comply with all applicable power quality standards. Furthermore, the replacement of conventional charging methods with the bidirectional DAB converter will enhance the efficiency, flexibility and energy recovery potential of the charging process, particularly in V2G applications.

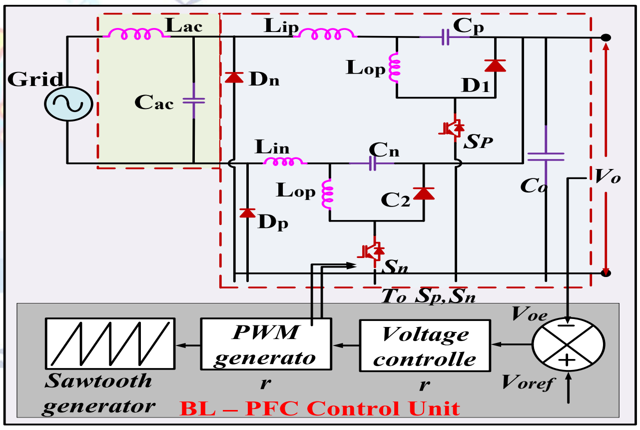


Fig. 2. Modified boost bridgeless PFC

B. Operating Principle

The proposed system's converters can be operated independently, but designed such that they will operate correctly with each portion of the input AC waveform. Therefore, a single converter will be conducting at a given time and the other will remain open circuit. A single switch will turn on for each positive half-cycle to allow the input to charge the inductor Lop and discharge the capacitor Cp. Energy will build up in the inductor. The associated diode will remain off since it is reversed biased. Once the switch is turned off the energy from the inductor Lop will begin to flow back into the dc-link. At the same time the capacitor Cp will begin to charge. As the cycle develops and the inductor has released all of its stored energy the system will enter a discontinuous conduction mode (dc-m). The inductor current will have reached zero and the dc-link capacitor will continue to supply power to the output. Since the inductor is in a dcm the output voltage will tend to be greater than what would be theoretically possible. This characteristic aids in reducing component size, lowering switching loss, and improving overall efficiency [6]. For the negative half-cycle of the input source a similar series of events will occur utilizing the lower side inductor and switch. The switch will turn on so that the inductor Lon may be charged and the capacitor discharged. Once the switch has turned off, the inductor will begin to discharge and the capacitor will begin to charge, just as occurred in the positive half-cycle. This symmetry results in an equivalent performance of the converters in both portions of the ac input wave form. Diodes Dp and Dn are used at the input stage to provide a means of transitionally connecting the two converters so that only one converter will be operational at any given time, thus eliminating any possibility of an improper or overlapping operation. Both diodes are essential to providing the required synchronized operation and stable power conversion process. Each switching component will be coordinated to complete their switching actions over the full range of input voltage and switching cycles, resulting in a highly efficient, low harmonic distorted output and regulated output for electric vehicle battery charging.

The BL converter design, which operates at power Pi, is accomplished by operating the inductors at a discontinuous conduction mode (dc-m). Hence, the inductor current i(Lopn,) will reach zero at some point in each switching cycle. While the intermediate capacitors Cp and Cn will be designed to operate in the continuous conduction mode (ccm), therefore keeping the source waveform stabilized.

$$v_s(t) = V_{s\_pk}\sin(2\pi f_L t) = 78 \times \sqrt{2}\sin(2\pi \times 50 \times t) \quad (1)$$

The representation of input frequency (Hz) and the maximum source voltage is given by f_L and V_{s_pk}, respectively. Also, input voltage (Vin) is given by:

$$v_{in}(t) = |V_{s\_pk}\sin(\omega_L t)| = |78\sqrt{2}\sin(314t)| \quad (2)$$

In the BL converter, the dc-link voltage (V_o) is given by:

$$V_o = \frac{1}{1-D} * V_{in} \quad (3)$$

Here, the duty ratio of the BL PFC converter is termed as D, which controls intermediate dc voltage. It is given as

$$D = \frac{V_o - V_{in}}{V_0} \quad (4)$$

The duty cycle range has been established between 0.39 (Da) and 0.15 (Db), which allows for a broad variety of input voltages to be accommodated throughout the charging process, equivalent to root-mean-square (rms) input voltage range of 65V (lowest) to 90V (highest).

1) Design of Input Inductor: The input inductors Lip and Lin are operated in the CCM so that there is an improvement in the input stability.

$$L_{ip}(= L_{in}) = \frac{v_{in}D}{0.2 i_{L_{ip}} f_{sL}} = \frac{R_{in}D_a}{0.2 f_{sL}} = \left(\frac{V_{smin}^2}{Pi}\right)\frac{D_a}{0.2 f_{sL}}$$

$$L_{ip}(= L_{in}) = \left(\frac{V_{smin}^2}{Pi}\right)\frac{1}{0.2 * f_{sL}}\frac{V_o - V_S}{V_o} \quad (5)$$

2) Energy Transfer Capacitance Design: To enable the transfer of energy with maximum voltage and achieve maximum ripple in capacitor voltage, an intermediate capacitor is utilized.

$$C_P(= C_{in}) = \frac{V_0}{\gamma\sqrt{2}V_{smax} f_{sL}(V_o^2/P_i)}\frac{V_o - \sqrt{2}V_{smax}}{V_o} \quad (6)$$

3) Design of Output Inductor: The output inductors Lop and Lon are designed to keep the ripple current nearly equal to twice the output current.

$$L_{opc}(= L_{onc}) = \frac{V_{in} * D_a}{2 * i_{Li} * f_{sL}} = \frac{R_{in} * D_a}{2 * f_{sL}} \quad (7)$$

The design calculation of the output inductor Lop,n to operate in the discontinuous inductor current mode is outlined as follows:

$$L_{op} = L_{opc} \quad (8)$$

4) Intermediate DC-Link Capacitor Design Co: The design of intermediate dc-link capacitor is Co, written as follows:

$$C_0 = \frac{I_o}{2\omega_L \Delta V_o} = \frac{(P_i/V_o)}{2\omega_L \Delta V_o} = \frac{P_i}{2 * \omega_L * \Delta V_o^2} \quad (9)$$

5) Line Filter Design: In order to avoid higher order harmonics occurring due to high-frequency switching at the source end, an LC filter as low-pass is cascaded just after the source voltage; the filter capacitor Cac is given by:

$$C_{aC\max} = \frac{I_{s-pk}}{\omega_L V_{s-pk}}\tan\theta = \frac{(P_i\sqrt{2}/V_S)}{(\omega_L\sqrt{2}V_S)}\tan(\cos^{-1} DPF) \quad (10)$$

4. DESIGN OF WPT DUAL ACTIVE BRIDGE CONVERTER

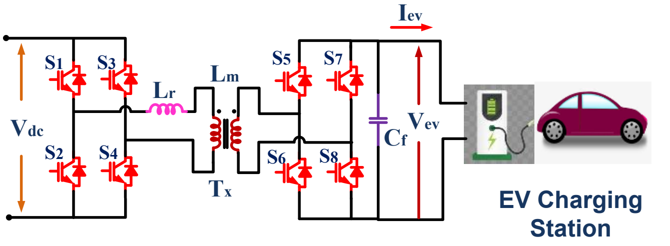


Fig.3 Designing of wireless dual active bridge converter for EV charging

Wireless Power Transfer (WPT) Dual Active Bridge (DAB) Converter is a high frequency, bidirectional DC-DC converter developed for use in electric vehicle (EV) fast charging applications. The WPT-DAB converter has two full bridge active circuits, a high frequency (HF) transformer, and a resonant circuit; this configuration provides for soft-switching of the devices to reduce loss. High frequency (typically between 85 kHz and 150 kHz) operation allows for reduced transformer size and minimizes energy loss as depicted in Figure [3]. The primary and secondary full bridges produce high frequency alternating current (AC) signals that are transmitted via the transformer and then rectified into DC at the load. Phase-shift modulated control is commonly employed in DAB converters to allow for precise control of the power flow while achieving zero-voltage switching (ZVS) for increased efficiency. A resonant tank circuit composed of inductance (Lr) and capacitance (Cr) provides for the soft-switching of the converter's power semiconductor devices.

The process of designing the WPT-DAB converter includes selecting the appropriate turns ratio (n) of the transformer, identifying the optimal switching frequency (fs) and determining the necessary values of the resonant inductance (Lr) and resonant capacitance (Cr) to provide for consistent power delivery. The DC-link voltage is controlled using a frequency control algorithm, which adjusts the frequency of operation based on the deviation from the resonant frequency to improve the overall efficiency. The controller employs phase shift modulation (PSM) to control the power flow by adjusting the phase difference (ϕ) between the primary and secondary full bridges. When the SOC of the EV battery is low, the controller will reduce the operating frequency to lower the input voltage to maintain efficient charging conditions. Additionally, the converter maintains operation away from series resonance under AC mains high voltage changes to guarantee reliability. The mathematical expression describing the WPT-DAB converter relates to the power transfer and soft-switching conditions of the converter. The power delivered to the load (P) in relation to the phase shift (ϕ) between the two bridges and the resonant circuit parameters is described mathematically by:

$$P = \frac{V_1 V_2}{n L_r f_s}\phi(1-\phi) \qquad (11)$$

where V1 and V2 are the primary and secondary voltages, nnn is the transformer turns ratio, Lr is the resonant inductor, and fs is the switching frequency. The resonant frequency is given by:

$$f_r = \frac{1}{2\Pi\sqrt{L_r C_r}} \qquad (12)$$

ensuring that the system operates in the optimal soft-switching region. The phase shift (ϕ) control is essential for adjusting power flow dynamically, maintaining efficient energy transfer. The zero-voltage switching (ZVS) condition is achieved when:

$$\phi \geq \frac{L_r I_0}{V_1} \qquad (13)$$

where Io is the output current. By implementing these control strategies, the WPT-DAB converter significantly improves power transfer efficiency, reduces switching losses, and ensures fast and flexible EV charging with minimal stress on power components.

5. CONTROL ALGORITHM

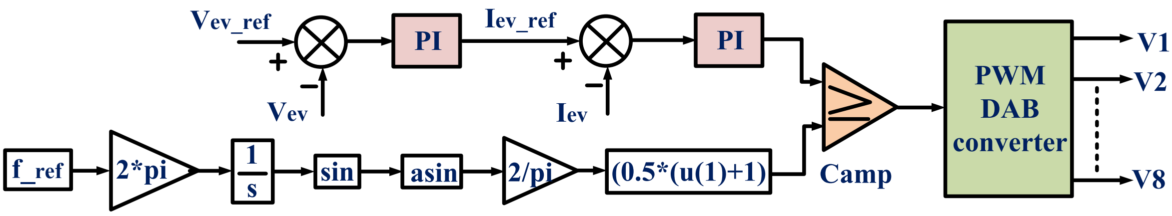


Fig.4 controller design for dual active bridge converter for fast electric vehicle charging station

1. Power Flow from Primary to Secondary (Charging Mode):

- Occurs when the primary voltage leads the secondary voltage (positive phase shift).
- Energy flows from DC source/grid to battery.

2. Power Flow from Secondary to Primary (Discharging Mode):

- Occurs when the secondary voltage leads the primary voltage (negative phase shift).
- Energy flows from battery to DC grid or loads.

This phase-shift control enables bidirectional power transfer with high efficiency, fast response, and soft-switching (ZVS).

a. Power Transfer Equation:

The average power transferred from primary to secondary is:

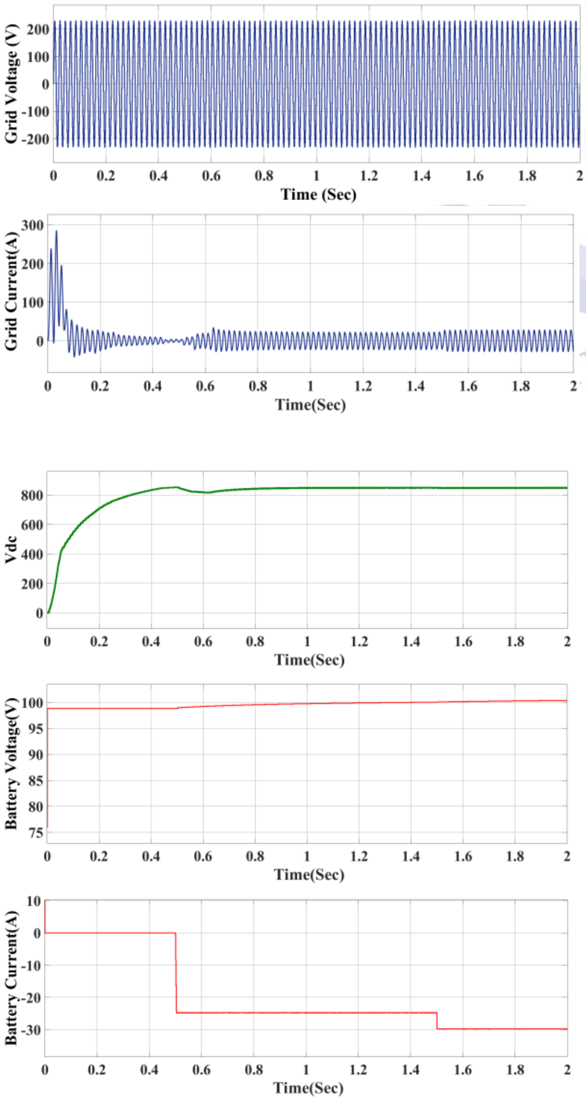
$$P = \frac{nV_1V_2}{\omega L} \cdot \phi \cdot \left(1 - \frac{|\phi|}{\pi}\right) \text{ (for small } \phi\text{)} \qquad (14)$$

Where:

- $\omega = 2\pi fs$
- $\phi \in [-\pi, \pi]$

6. RESULTS AND DISCUSSION

The performance of the proposed electric vehicle (EV) battery charging system is supported by both simulated and hardware prototype models that were compared under various types of loads and grid conditions. Performance evaluation criteria include input power factor, total harmonic distortion (THD) of input current, regulation of DC-link voltage, charging curve accuracy in Constant Current (CC) and Constant Voltage (CV) modes, bi-directional power flow, and component thermal characteristics. Using the traditional method with a flyback converter and a standard control device as a base case, simulated results indicate that the power factor of the input remained significantly less than one, especially when the EV charging current was very low (e.g., under partial or low-load conditions). Additionally, the simulated input current waveforms had significant THD and did not comply with IEC 61000-3-2 requirements. The flyback converter has been effective for simple EV charging applications; however, it was shown to have substantial loss in the transformer and switching devices under high EV charging currents, resulting in poor overall system efficiency and limited scalability. On the other hand, the proposed bridgeless boost converter combined with a digital Power Factor Correction (PFC) control technique provided a nearly-unity input power factor for a wide range of input voltages and state-of-charge (SOC) levels of the EV battery. The digital PFC controller was able to shape the input current waveform into a sinusoidal waveform in-phase with the grid voltage, thereby reducing the harmonic distortion and reactive power demand. Total harmonic distortion values of less than 5% were demonstrated by simulation results, thus meeting the requirements of IEC 61000-3-2 and IEEE 519 [2] standards. The DC-link voltage was well-regulated by the PFC stage with minimal overshoot and rapid settling times due to the step-load variations. The intermediate stage maintained a stable reference voltage, which was then processed by the Dual Active Bridge (DAB) Converter to provide controlled charging power to the EV battery. The DAB stage was found to exhibit excellent dynamic performance and executed Phase Shift Modulation (PSM) to manage bidirectional power flow. Simulations of both Grid-to-Vehicle (G2V) operation (i.e., battery charging) and Vehicle-to-Grid (V2G) operation (i.e., energy export from the battery back to the grid) were performed. The battery charging profile was demonstrated to follow the prescribed constant current and constant voltage trajectories safely and efficiently during G2V operation. When the battery reached full charge, the converter automatically switched from CC to CV mode accurately regulating the output voltage and minimizing the ripple. V2G operation simulations were also conducted where the DAB converter successfully returned energy from the battery to the grid through the regulated DC link. This demonstrated the bidirectional capabilities of the system. Transitioning between the two power flow directions was smooth due to the precise phase shift control of the dual bridges and coordinated gate drive circuitry. Measured efficiencies indicated that the DAB stage had operating efficiencies greater than 94% under normal conditions, with Zero Voltage Switching (ZVS) soft-switching being observed over most of the operating load points. These efficiencies contributed to lower switching losses and improved thermal behavior. Optionally, an additional LLC Resonant Stage was included in the simulations. The resonant stage further minimized the output voltage ripple, specifically under low-load conditions, and improved Electromagnetic Compatibility (EMC) by limiting high-frequency switching noise. Testing of a scaled-down version of the proposed charging system hardware prototype corroborated the simulation results. The testbed consisted of voltage and current sensing devices, temperature monitoring, and real-time data logging via a microcontroller-based digital control unit. Observations made from the oscilloscope verified that the input current waveform was sinusoidal and in-phase with the grid voltage, verifying the correct functioning of the PFC algorithm. The thermal imaging and current probes revealed balanced thermal distribution across MOSFETs and transformer windings without forming hotspots. The charging curves obtained during the hardware tests matched the expected CC and CV charging curves, and the SOC readings from the battery management system confirmed the accurate delivery of energy.



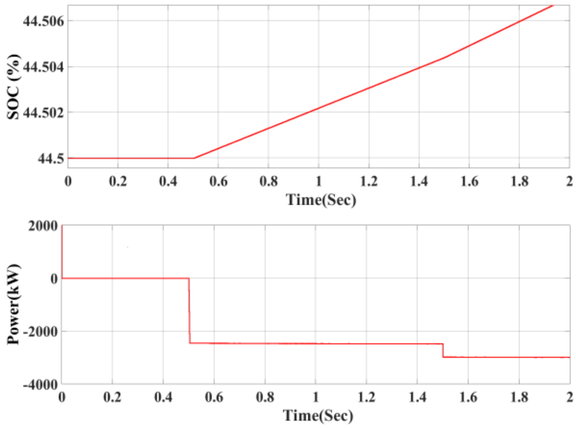


Fig. 5 Simulation Results of Bidirectional DC-DC Dual-Active Bridge Converter with PFC BL-Modified Boost Converter

Overall, the results strongly indicate that the proposed system significantly outperforms the traditional flyback-based method across all critical parameters. It achieves high efficiency, compliance with power quality standards, enhanced control, and bidirectional functionality, making it a suitable candidate for next-generation smart grid compatible electric vehicle charging infrastructure.

7. CONCLUSION

The purpose of this study is to design and test a novel charging method for Electric Vehicles (EVs) by means of a bridgeless power factor correction (PFC) stage followed by a bidirectional dual active bridge (DAB) converter which is capable of bidirectional energy exchange between the grid and the EV battery, in addition to achieving near unity power factor, low conduction losses and low input current distortion at the same time. Using MATLAB based simulation we will also be able to test the efficiency and ability of the system to meet the required power quality standards (IEC 61000-3-2 and IEEE 519). The bridgeless PFC configuration reduces conduction loss in comparison with the traditional diode rectifier and has the capability of near unity power factor operation. The use of a digital PFC controller enabled us to create an input current that closely follows the waveform of the grid voltage, thus enabling us to comply with the international power quality standards mentioned above. In addition to the PFC stage the bidirectional DAB stage provides galvanic isolation and enables us to have both grid to vehicle (G2V) and vehicle to grid (V2G) power exchange capabilities. The DAB stage is controlled using phase shift modulation to enable both soft and efficient switching operation. We will also be testing all performance characteristics of the system using MATLAB simulation, specifically: DC link voltage regulation, input current distortion, and charging profile accuracy. The results from our simulations confirm that the system operates stably under variable load conditions while providing high efficiency and low harmonic distortion levels. The system is a simulated model and was not implemented as a physical prototype. Our simulation results demonstrate the feasibility of the system for future smart charging stations and grid connected electric vehicle infrastructure. The modular nature of the design and the scalable architecture combined with the systems ability to meet the required power quality standards makes it a good candidate for future generations of electric vehicles.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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