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Enhance Grid Power Quality of Bidirectional Transformer Less Electric Vehicle Charging

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ABSTRACT
The rapid proliferation of electric vehicles (EVs) demands high-performance charging systems that not only ensure efficient energy transfer but also maintain superior grid power quality. Conventional EV chargers, particularly those employing transformer-based or unidirectional rectifiers, suffer from increased size, cost, and significant power quality issues such as high Total Harmonic Distortion (THD), poor power factor, and switching losses. To address these challenges, this paper proposes a transformer-less bidirectional EV charging system based on a 4-switch 3-level H-bridge rectifier topology aimed at enhancing grid power quality and system efficiency.
The proposed configuration reduces the number of power switches compared to traditional 6-switch converters, thereby minimizing switching losses, conduction losses, and overall system complexity. The 3-level operation enables better voltage waveform approximation, resulting in reduced harmonic distortion and improved power factor. Additionally, the transformer-less structure significantly decreases system size, weight, and cost, while improving overall efficiency. The bidirectional capability supports both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations, enabling effective energy exchange and grid support functionalities.
To further enhance performance, advanced control strategies such as sinusoidal pulse width modulation (SPWM) and power factor correction (PFC) are incorporated to ensure near-unity power factor and low THD in grid current. The system also maintains stable DC-link voltage and ensures safe operation under varying load and grid conditions. Comparative analysis demonstrates that the proposed 4-switch 3-level H-bridge rectifier achieves superior performance in terms of harmonic reduction, efficiency improvement, and power quality enhancement when compared with conventional topologies.
Overall, the proposed transformer-less bidirectional EV charging system presents a compact, cost-effective, and energy-efficient solution for next-generation smart grid applications, contributing to improved power quality, reduced losses, and sustainable EV integration.
Keywords: Electric Vehicles (EVs), Grid-to-Vehicle, Power Quality

1. INTRODUCTION
The rapid growth of electric vehicles (EVs) has intensified the need for efficient, compact, and grid-friendly charging systems. As EV penetration increases, the impact of charging infrastructure on the electrical grid becomes more significant, particularly in terms of power

quality. Poor power quality—characterized by high Total Harmonic Distortion (THD), low power factor, and voltage fluctuations—can lead to increased losses, overheating of equipment, and reduced overall system reliability. Therefore, enhancing grid power quality has become a critical requirement in the design of modern EV charging systems [1].

Conventional EV chargers typically employ transformer-based rectifiers to provide galvanic isolation and voltage matching. However, these systems are bulky, costly, and less efficient due to additional magnetic components and associated losses. Moreover, traditional unidirectional rectifiers introduce significant harmonic distortion and do not support reverse power flow, limiting their capability for advanced applications such as Vehicle-to-Grid (V2G). In contrast, transformer-less bidirectional converters offer a more compact and efficient solution, enabling both Grid-to-Vehicle (G2V) and V2G operations while reducing system size, weight, and cost [2, 3].

Among various converter topologies, multilevel converters have gained attention due to their ability to generate high-quality output waveforms with lower harmonic distortion and reduced switching stress. In particular, the 3-level H-bridge rectifier provides improved voltage resolution compared to conventional two-level converters. However, standard multilevel topologies often require a larger number of power switches, increasing circuit complexity and control requirements. To overcome this limitation, the 4-switch 3-level H-bridge rectifier has been proposed as an efficient alternative that reduces the number of switches while maintaining the advantages of multilevel operation [4].

The transformer-less 4-switch 3-level H-bridge rectifier offers several benefits, including reduced switching and conduction losses, improved efficiency, and lower implementation cost. Its bidirectional capability allows seamless transition between charging and discharging modes, supporting grid stabilization and energy management. Additionally, the multilevel structure helps in minimizing THD and improving input current quality, which are essential for compliance with power quality standards [5, 6].

To fully exploit the advantages of this topology, advanced control techniques such as sinusoidal pulse width modulation (SPWM), power factor correction (PFC), and closed-loop voltage control are employed. These strategies ensure near-unity power factor, stable DC-link voltage, and reduced harmonic content under varying operating conditions. Furthermore, the elimination of bulky transformers enhances power density and makes the system more suitable for modern compact EV charging applications [7].

This work focuses on the design and analysis of a transformer-less bidirectional EV charging system based on a 4-switch 3-level H-bridge rectifier aimed at enhancing grid power quality. The study evaluates the performance of the proposed system in terms of THD reduction, efficiency improvement, and power factor enhancement, demonstrating its suitability for next-generation smart grid and EV integration applications [8].

2. ELECTRIC VEHICLE CHARGING

Transformer-less Electric Vehicle (EV) charging systems are advanced charging technologies designed to charge electric vehicles without using bulky line-frequency transformers. Conventional EV chargers generally use transformers for voltage isolation, safety, and power conversion, but these transformers increase system size, weight, cost, and power losses. To overcome these limitations, transformer-less charging architectures are developed to provide compact size, higher efficiency, lower cost, and improved power density for modern EV charging applications [9, 10].

In a transformer-less EV charger, power conversion is achieved using power electronic converters such as AC-DC rectifiers, DC-DC converters, and inverter circuits without magnetic isolation at the grid frequency stage. These chargers directly convert the grid AC supply into the required DC charging voltage for the EV battery using high-speed switching devices like MOSFETs and IGBTs. Since the transformer is eliminated, conduction and core losses are significantly reduced, resulting in higher overall efficiency and faster charging performance. Transformer-less chargers are therefore widely preferred in lightweight and portable charging infrastructures [11].

The major advantage of transformer-less charging systems is their high efficiency, typically above 95%, due to reduced conversion stages and minimized magnetic losses. They also offer reduced hardware complexity, compact structure, low manufacturing cost, and improved thermal performance. These features make them highly suitable for residential charging stations, commercial EV infrastructure, smart grids, and renewable-energy-based charging applications. In addition, transformer-less topologies support bidirectional power flow, enabling Vehicle-to-Grid (V2G) operation where EV batteries can supply power back to the utility grid during peak demand conditions [12, 13].

However, transformer-less EV charging systems also face several technical challenges. Since galvanic isolation is absent, leakage current and safety issues become important concerns. Common-mode leakage currents may occur due to parasitic capacitances between the vehicle body and the grid, which can affect user safety and electromagnetic compatibility. Therefore, advanced control strategies, grounding techniques, and leakage current suppression methods are required to ensure safe operation. Researchers also focus on reducing harmonic distortion, improving power factor correction, and enhancing grid synchronization for efficient charging performance [14].

3. PROPOSED METHODOLOGY

The proposed methodology focuses on the design and implementation of a transformer-less bidirectional EV charging system using a 4-switch 3-level H-bridge rectifier to enhance grid power quality, reduce system complexity, and improve overall efficiency. The approach integrates an optimized converter topology with advanced control techniques to achieve low harmonic distortion, near-unity power factor, and reliable bidirectional power flow.

Initially, the system is modeled as a single-phase grid-connected converter interfaced with an EV battery through a DC-link capacitor. The proposed 4-switch configuration reduces the number of active switches compared to conventional 6-switch topologies, thereby minimizing switching losses and simplifying the gate driving circuitry. The 3-level operation is achieved by appropriately controlling the switching states to generate three distinct voltage levels (+Vdc, 0, −Vdc), which improves the quality of the input current waveform and reduces Total Harmonic Distortion (THD).

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The operation of the system is divided into two modes: Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G). In G2V mode, the rectifier converts AC grid power into regulated DC power for charging the EV battery. In V2G mode, the stored energy in the battery is fed back to the grid, and the converter operates as an inverter. A seamless transition mechanism between these two modes is implemented to ensure stable and continuous operation [15, 16].

To enhance power quality, a control strategy based on Sinusoidal Pulse Width Modulation (SPWM) combined with Power Factor Correction (PFC) is employed. A reference sinusoidal current is generated in phase with the grid voltage, and a current control loop ensures that the input current follows this reference accurately. This results in near-unity power factor and significant reduction in harmonic components. Additionally, a closed-loop voltage controller is used to maintain a constant DC-link voltage under varying load and grid conditions.

For further performance improvement, a Proportional-Integral (PI) controller is implemented to regulate both current and voltage loops. The controller parameters are optimized to achieve fast dynamic response, minimal steady-state error, and system stability. The switching signals for the 4-switch H-bridge are generated based on the comparison of reference signals with high-frequency carrier waves in the SPWM technique.

To validate the effectiveness of the proposed system, simulation is carried out using MATLAB/Simulink. Key performance parameters such as THD, power factor, efficiency, and DC-link voltage stability are analyzed under different operating conditions. Comparative evaluation with conventional rectifier topologies demonstrates that the proposed 4-switch 3-level H-bridge rectifier significantly improves power quality while reducing system complexity and losses.

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 [17, 18].

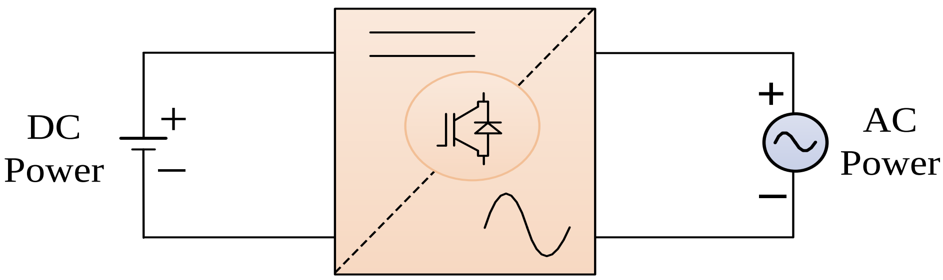

Figure 1: Basic diagram of DC-AC Inverter

AC-DC Rectifier

Direct current (DC) output power is produced by a rectifier using alternating current (AC) input power as input.

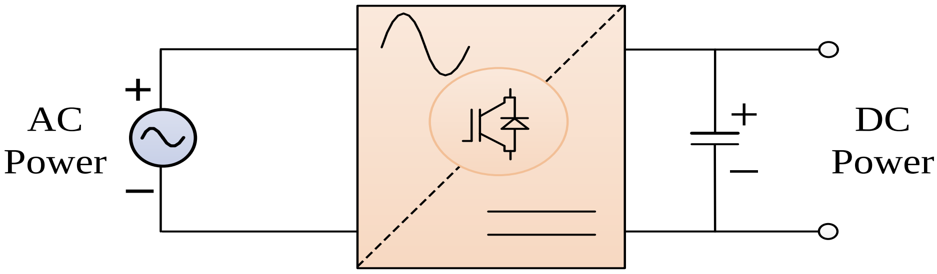

Figure 2: Basic diagram of AC-DC Rectifier

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 2. 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 [19].

H-Bridge Inverter

An H-bridge converter consists of a single DC source and four semiconductor switches like IGBTs or MOSFETs. The activity of H-span rectifier relies on the exchanging of the four switches. There are four series-paired switches in the structure. Figure 3 depicts the H-bridge inverter's circuit diagram.

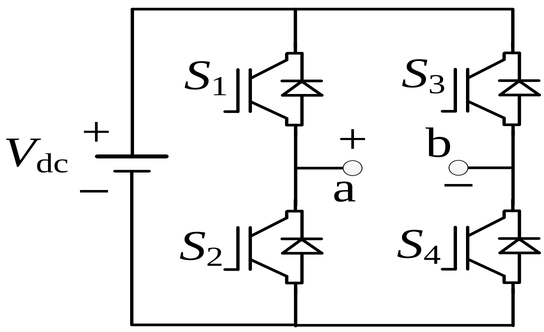

Figure 3: Inverter topology for H-bridge

The converter system's gain, which also reflects the modulation index, is calculated by taking into account the voltages at the input and output. The H-bridge inverter has a gain of 1. This type of converter produces three voltage levels, Vdc, 0 and -Vdc, as the name suggests [20].

A full-bridge inverter with IGBTs is also known as an H-bridge because of where its power switches are positioned. The inverter can handle both reactive and real power. The second leg has a 180-degree delay in the switching mechanism compared to the first leg. The heap exists between two midpoints of the legs.

Because a short-circuit would be created across the DC link, switched S1 and S2 (as well as S3 and S4) cannot be turned on simultaneously. The exchanging conditions of the H-span inverter are determined in Table 1.

Table 1: H-bridge inverter of Switching states

State	V_{ab}	S_1	S_2	S_3	S_4
1	$+V_{dc}$	1	0	0	1
2	0	1	0	1	0
3	0	0	1	0	1
4	$-V_{dc}$	0	1	1	0

The changing of the switching pulse results in the generation of three distinct output voltages. Flows are used to describe levels:

State 1 (level +V_dc): By turning on switches S1 and S4 input voltage source is associated with the result terminal and produces Vdc.

Stage 2 and 3 (0 level): By activating switches S2, S4, or S1 and S3, the output terminal generates a zero voltage in one of two ways. The generated output voltage is zero because the DC source is bypassed in both instances.

State 4 (〖-V〗_dc level): The negative-polarity input voltage source is connected to the negative-polarity output terminal by activating switches S2 and S3.

4. 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.

Table 2: 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.

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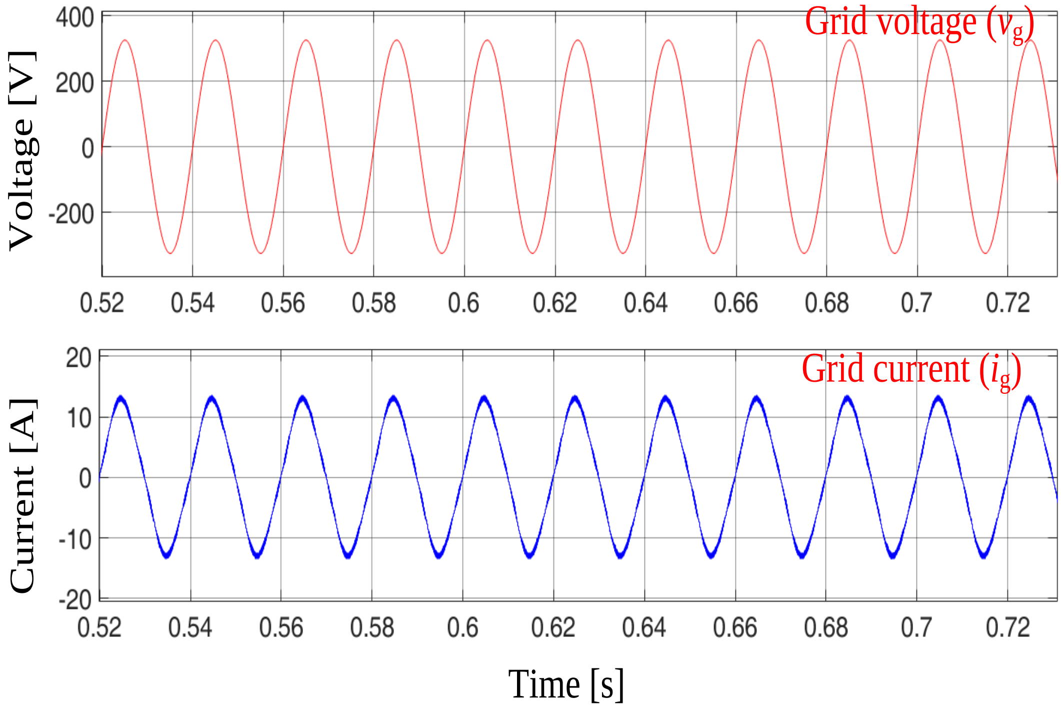

Figure 4: Rectifier input voltage and current for DC load

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.

The figure illustrates the waveform analysis of grid voltage $(v_g)$and grid current $(i_g)$with respect to time. The upper graph represents the grid voltage waveform, while the lower graph represents the grid current waveform. The grid voltage waveform is sinusoidal in nature with a peak amplitude of approximately ±320 V, indicating a stable AC supply condition. Similarly, the grid current waveform also follows a sinusoidal pattern with a peak value of nearly ±15 A. Both voltage and current signals exhibit periodic behavior over the observed time interval from 0.52 s to 0.72 s, confirming proper synchronization between the grid parameters.

The waveforms demonstrate that the current is nearly in phase with the voltage, which indicates a good power factor and efficient power transfer between the converter and the electrical grid. The smooth sinusoidal nature of the current waveform also suggests reduced harmonic distortion and improved power quality. Such characteristics are highly desirable in

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grid-connected power electronic systems, renewable energy integration, and inverter applications. The stable amplitude and frequency response confirm reliable system operation and effective control of the grid interface under steady-state conditions.

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° 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° 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.

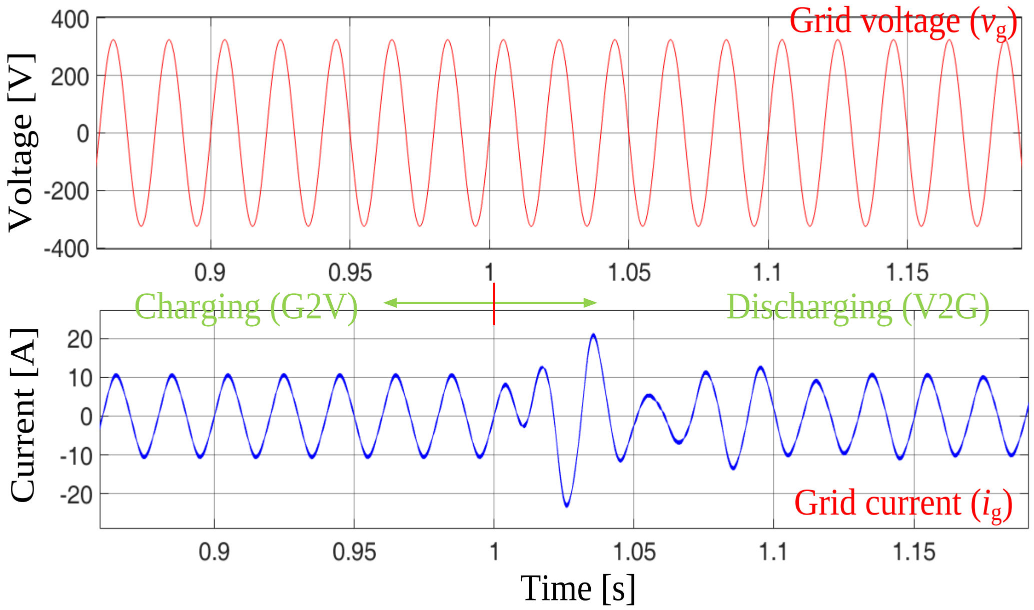

Figure 5: Grid voltage and grid current to verifying the charging and discharging mode

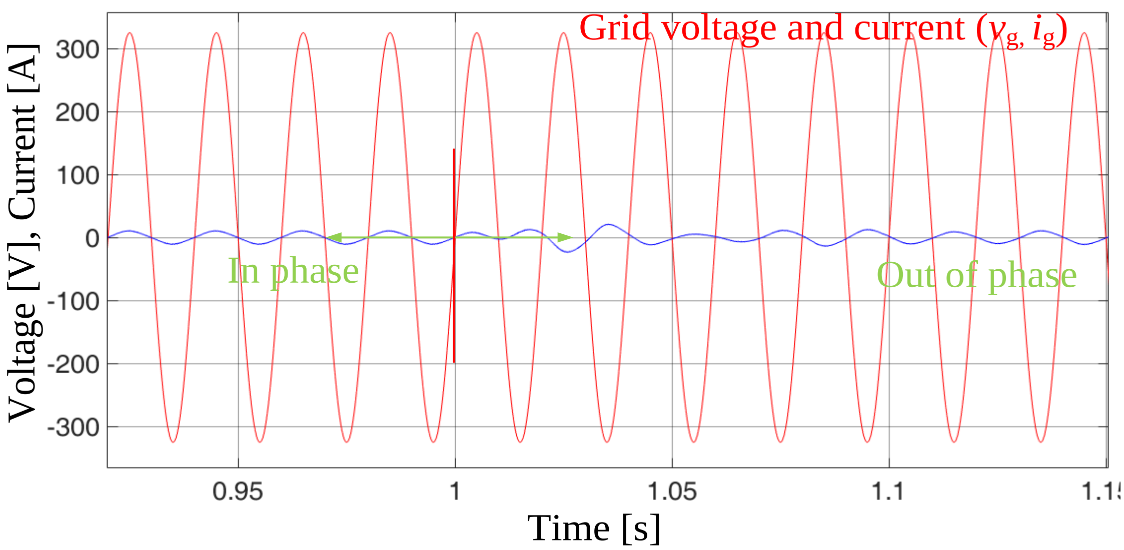

Figure 6: Grid voltage and grid current to validate PFC

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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 6 shows the rectifier regulated voltage, battery voltage and battery current for charging and discharging mode of operation.

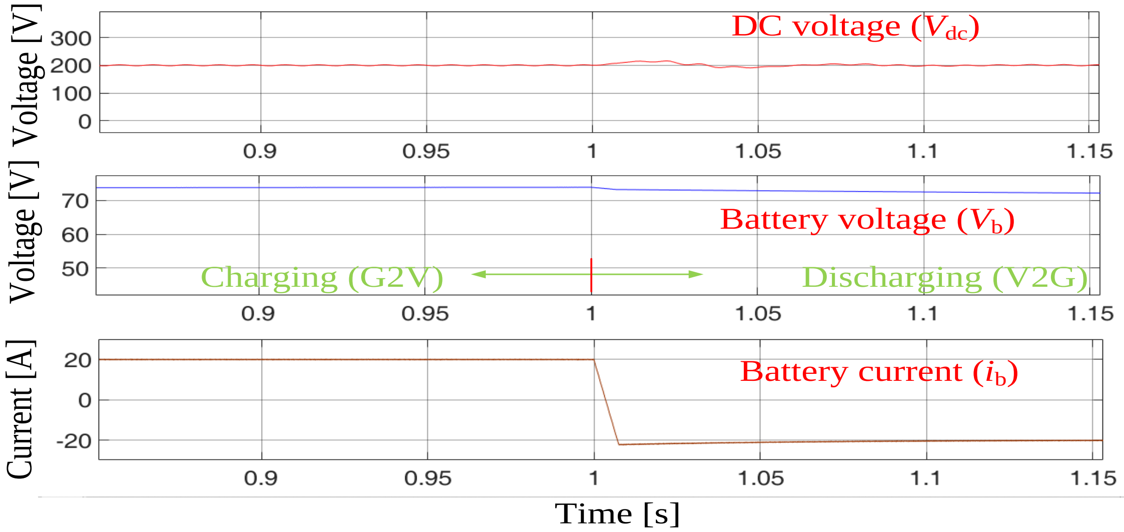

Figure 7: V2G operation with output voltage of rectifier, battery voltage and battery current for charging and discharging mode

For charging mode state of charge (SOC) is increases and for discharging process SOC is decreases. Figure 7 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.

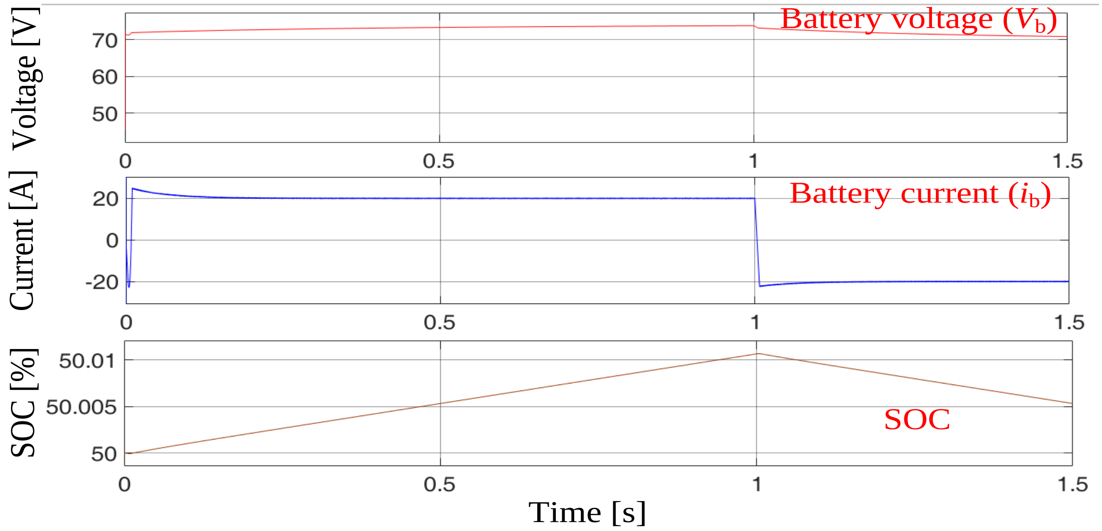

Figure 8: V2G operation with battery voltage, battery current and state of charge (SOC)

5. CONCLUSIONS

The proposed transformer-less bidirectional EV charging system based on a 4-switch 3-level H-bridge rectifier presents an effective solution for enhancing grid power quality while maintaining high efficiency and reduced system complexity. By eliminating the transformer, the overall size, cost, and losses of the system are significantly reduced, making it more suitable for modern compact and high-performance EV charging applications.

The use of a 4-switch configuration minimizes switching and conduction losses compared to conventional topologies, while the 3-level operation improves the quality of voltage and current waveforms. This results in lower Total Harmonic Distortion (THD) and improved power factor, ensuring better compliance with grid standards. Additionally, the bidirectional capability supports both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations, enabling efficient energy exchange and contributing to grid stability.

The integration of advanced control strategies such as Sinusoidal Pulse Width Modulation (SPWM), Power Factor Correction (PFC), and PI controllers further enhances system performance by ensuring stable DC-link voltage, accurate current tracking, and fast dynamic response under varying operating conditions. These features collectively improve the reliability and robustness of the charging system.

In conclusion, the proposed topology offers a compact, cost-effective, and energy-efficient approach for next-generation EV charging systems. It successfully addresses major power quality challenges while supporting smart grid integration, making it a promising candidate for sustainable and intelligent electric vehicle infrastructure.

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