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Survey Paper on 5-Level Bidirectional PFC Rectifier for V2G Application

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ABSTRACT

The rapid growth of electric vehicles (EVs) and the emergence of Vehicle-to-Grid (V2G) technology have created a strong demand for efficient, bidirectional power conversion systems. This survey paper presents a comprehensive review of 5-level bidirectional Power Factor Correction (PFC) rectifiers designed for V2G applications. The study explores various multilevel converter topologies, including neutral-point clamped, flying capacitor, and cascaded H-bridge configurations, highlighting their suitability for bidirectional energy flow between EV batteries and the grid. Emphasis is placed on the ability of 5-level PFC rectifiers to achieve high power quality, reduced total harmonic distortion (THD), and near-unity power factor under both charging (grid-to-vehicle) and discharging (vehicle-to-grid) modes. Furthermore, the paper examines different control strategies such as conventional PI control, model predictive control, and intelligent techniques to ensure stable and efficient bidirectional operation. Key design challenges including switching losses, voltage balancing, control complexity, and system reliability are also critically analyzed. The survey demonstrates that 5-level bidirectional PFC rectifiers offer significant advantages over conventional two-level converters, including improved efficiency, lower electromagnetic interference, and enhanced grid compatibility. Finally, future research directions are outlined, focusing on advanced modulation techniques, integration with renewable energy sources, and the application of machine learning for adaptive control in V2G systems.

Keywords: Electrical Vehicles, Battery Management System, Battery Model

I. INTRODUCTION

The increasing penetration of electric vehicles (EVs) and the evolution of smart grid technologies have accelerated the need for efficient and intelligent power conversion systems. One of the most promising concepts in this domain is Vehicle-to-Grid (V2G), which enables bidirectional energy flow between EV batteries and the utility grid. In this framework, electric vehicles not only consume energy during charging but also supply power back to the grid during peak demand, thereby improving grid stability, load balancing, and energy utilization. To effectively implement V2G systems, advanced power electronic converters are required that can ensure high efficiency, low harmonic distortion, and reliable bidirectional operation [1, 2].

A 5-level bidirectional Power Factor Correction (PFC) rectifier has emerged as a highly suitable solution for such applications. Unlike conventional two-level converters, multilevel rectifiers generate output voltage in multiple discrete levels, which significantly reduces switching stress, electromagnetic interference (EMI), and total harmonic distortion (THD). The 5-level topology, in particular, provides a balanced trade-off between circuit complexity and performance improvement. It enhances the quality of input current by maintaining near-unity power factor while enabling smooth bidirectional power flow between the grid and the EV battery [3].

In V2G applications, the rectifier operates in two modes: Grid-to-Vehicle (G2V) mode, where power flows from the grid to charge the EV battery, and Vehicle-to-Grid (V2G) mode, where stored energy is fed back into the grid. The bidirectional PFC rectifier plays a crucial role in both modes by regulating voltage, shaping current, and ensuring compliance with grid standards. Additionally, advanced control strategies such as PI controllers, predictive control, and intelligent optimization techniques are often integrated to maintain voltage balancing across multiple levels and to improve dynamic performance.

Despite its advantages, the design of a 5-level bidirectional PFC rectifier involves several challenges, including increased control complexity, capacitor voltage balancing issues, and switching losses. However, ongoing research in modulation techniques, semiconductor devices, and intelligent control algorithms continues to enhance the performance and feasibility of these systems for real-world V2G deployment [4, 5].

II. LITERATURE REVIEW

Srinu Ruttala et al. [1], proposed a novel 5-level bidirectional PFC buck rectifier employing switched capacitor technology to address the challenges of dynamic loads and scalability in modern power systems. The key contribution of this work lies in its ability to achieve multilevel voltage generation with reduced component count while maintaining high efficiency and power factor correction. The switched capacitor configuration enables flexible voltage scaling, making the topology highly suitable for electric vehicle (EV) and Vehicle-to-Grid (V2G) applications. Additionally, the proposed system demonstrates improved performance under varying load conditions, reduced switching losses, and better voltage stress distribution across devices. The study also highlights the rectifier's capability to operate efficiently in bidirectional mode, ensuring seamless transition between charging and discharging operations, which is critical for smart grid integration.

A. Jain et al. [2], introduced a novel single/multiple output multilevel buck rectifier specifically designed for EV battery charging applications. Their work focuses on improving charging flexibility by enabling multiple output ports, which can support simultaneous charging of different battery modules. The multilevel structure significantly reduces output voltage ripple and enhances efficiency compared to traditional converters. Furthermore, the proposed topology ensures high power quality and reduced harmonic distortion, making it compliant with grid standards. The authors also emphasize modularity and scalability, which are essential for next-generation EV charging infrastructure. Their results demonstrate that the converter achieves improved performance in terms of efficiency, voltage regulation, and system reliability.

Z. Chen et al. [3], developed a high power factor bridgeless integrated buck-type PFC converter with a wide output voltage range, targeting applications requiring flexible voltage control such as EV charging systems. The elimination of the diode bridge reduces conduction losses and improves overall efficiency. The integrated design simplifies the circuit structure while maintaining high power density and performance. The converter is capable of operating over a wide voltage range, making it suitable for varying battery charging requirements. Experimental results show near-unity power factor, reduced total harmonic distortion (THD), and improved thermal performance, demonstrating its effectiveness in high-performance power conversion systems.

M. Babaei et al. [4], proposed high step-down bridgeless SEPIC/Cuk PFC rectifiers aimed at improving efficiency and reducing current stress in power electronic systems. Their design combines the advantages of SEPIC and Cuk converters to achieve high voltage conversion ratios with minimal component stress. The bridgeless configuration further enhances efficiency by eliminating unnecessary conduction paths. The study provides a detailed analysis of current stress reduction, which leads to improved reliability and longer lifespan of components. The proposed topology is particularly beneficial for low-voltage EV battery charging applications where high step-down conversion is required.

Liwei Zhou et al. [5], presented the design of a transformer-less electric vehicle charger with symmetric AC and DC interfaces. This work focuses on reducing system size, weight, and cost by eliminating the transformer while maintaining safety and performance. The symmetric interface ensures balanced operation and reduces common-mode noise, which is crucial for grid compliance. The charger supports bidirectional power flow, making it compatible with V2G applications. The authors also discuss control strategies and system optimization techniques to enhance efficiency and reliability. Their design demonstrates significant improvements in power density and system integration.

C. J. R. Cortés et al. [6], provided a comprehensive review of power converters used for on-board EV battery charging systems. The paper analyzes various converter topologies, including isolated and non-isolated designs, highlighting their advantages and limitations. Key performance metrics such as efficiency, power density, cost, and complexity are discussed in detail. The authors emphasize the growing importance of bidirectional converters for V2G applications and the need for advanced control techniques to ensure stable operation. This review serves as a valuable reference for researchers by summarizing existing technologies and identifying future research directions.

N. Rana et al. [7], focused on the modeling, analysis, and implementation of an improved interleaved buck-boost converter. Their approach enhances power conversion efficiency and reduces ripple through interleaving techniques. The converter is designed to handle wide input and output voltage ranges, making it suitable for EV charging systems. The study also highlights improved dynamic response and reduced component stress. Experimental validation confirms the effectiveness of the proposed design in achieving high efficiency and reliable performance under varying operating conditions.

Z. Chen et al. [8], investigated bridgeless PFC topology simplification and design for performance benchmarking. The authors proposed simplified circuit configurations that reduce component count while maintaining high efficiency and power quality. Their work provides a comparative analysis of different PFC topologies, focusing on parameters such as THD, efficiency, and power factor. The study concludes that bridgeless configurations offer superior performance compared to conventional designs, making them ideal for EV and renewable energy applications.

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R. G. A. Subramanian et al. [9], developed a lead-acid battery charger using a modified bridgeless SEPIC PFC converter. The proposed system improves efficiency by reducing conduction losses and enhances power factor correction. The converter is designed to provide stable output voltage and current for battery charging applications. The authors also address issues related to switching losses and component stress, presenting a practical solution for low-cost and efficient battery charging systems.

E. Gumrukcu et al. [10], explored optimized load allocation in modular multilevel converter (MMC)-based EV charging infrastructure. Their work focuses on improving system efficiency and reliability by distributing loads optimally across multiple converter modules. The proposed approach enhances scalability and supports large-scale EV integration into the power grid. The study also highlights the importance of advanced control and optimization techniques in managing complex charging infrastructures, particularly for future smart grid and V2G applications.

III. PFC RECTIFIER

A Bidirectional Power Factor Correction (PFC) rectifier is an advanced power electronic converter that enables two-way energy flow between an AC source (such as the utility grid) and a DC load (such as an electric vehicle battery), while simultaneously maintaining a high power factor and low harmonic distortion. Unlike conventional rectifiers that only allow unidirectional power flow (AC to DC), bidirectional PFC rectifiers support both Grid-to-Load (G2L) and Load-to-Grid (L2G) operations, making them essential for modern applications like electric vehicles (EVs) and Vehicle-to-Grid (V2G) systems.

Working Principle:

The operation of a bidirectional PFC rectifier is based on controlled switching devices (such as MOSFETs or IGBTs) that regulate both voltage and current. It operates in two modes:

- Rectification Mode (G2V / Charging Mode): AC power from the grid is converted into DC power to charge the battery. The rectifier shapes the input current to be sinusoidal and in phase with the input voltage, achieving near-unity power factor.
- Inversion Mode (V2G / Discharging Mode): The stored DC energy in the battery is converted back into AC and supplied to the grid. In this mode, the rectifier behaves like an inverter while still maintaining power quality.

Key Features

- Bidirectional Power Flow: Enables both charging and discharging operations.
- Power Factor Correction: Maintains power factor close to unity.
- Reduced Harmonics: Minimizes Total Harmonic Distortion (THD) in input current.
- High Efficiency: Achieved through advanced switching and control techniques.
- Grid Compliance: Meets standards for modern smart grids and EV infrastructure.

The given circuit represents a bidirectional PFC (Power Factor Correction) rectifier topology, commonly used in applications like EV chargers and V2G systems. It consists of an AC source V_g, an input inductor L, two active switches $Q_1$and Q_2, two main power semiconductor switches $S_{D1}$and S_{D2}(typically MOSFETs with anti-parallel diodes), and an output DC-link capacitor $C_o$that provides a regulated DC output voltage V_o.

In operation, the input AC voltage $V_g$is first passed through the inductor L, which plays a crucial role in shaping the input current to be smooth and nearly sinusoidal, thereby achieving power factor correction. The switches $Q_1$and Q_2act as high-frequency control elements that regulate the current path depending on the switching strategy. The main switches $S_{D1}$and S_{D2}operate in a complementary manner to control energy transfer between the AC side and the DC side. During the positive half-cycle of the AC input, one switching path is activated (typically involving S_{D2}), allowing energy to flow into the DC-link capacitor C_o, while during the negative half-cycle, the other path (involving S_{D1}) conducts. This alternating operation ensures full-wave rectification with controlled switching rather than passive diode conduction.

The capacitor $C_o$filters the rectified voltage and maintains a stable DC output V_o, which can be used to charge a battery or supply a DC load. In bidirectional operation, the same circuit can reverse power flow by appropriately controlling the switches, allowing energy from the DC side to be fed back into the AC grid. Overall, this topology provides improved efficiency, reduced harmonic distortion, and near-unity power factor compared to conventional rectifiers, making it highly suitable for modern high-performance power conversion systems.

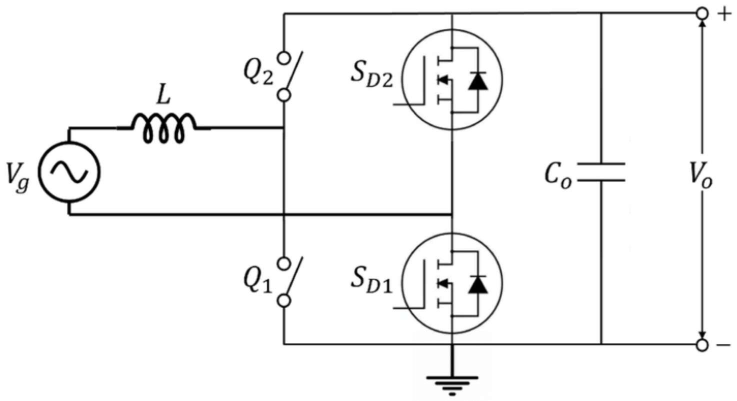

Fig. 1: Single Phase Bidirectional Rectifier

IV. V2G APPLICATION

In Vehicle-to-Grid (V2G) applications, the shown bidirectional PFC rectifier circuit plays a crucial role in enabling two-way energy exchange between the electric vehicle (EV) battery and the utility grid. The AC source $V_g$represents the grid, while the DC side with capacitor $C_o$corresponds to the EV battery system. The inductor Lensures smooth current shaping, which is essential for maintaining a high power factor and reducing harmonics during both charging and discharging operations.

During Grid-to-Vehicle (G2V) mode (charging), the circuit operates as an active rectifier. The AC power from the grid is converted into DC power using controlled switching of Q_1, Q_2, S_{D1}, and S_{D2}. The inductor Lhelps in shaping the input current to be sinusoidal and in phase with the grid voltage, achieving near-unity power factor. The energy is then stored in the DC-link capacitor $C_o$and supplied to charge the EV battery. The switching devices are controlled using PWM techniques to regulate voltage and current according to battery requirements.

In Vehicle-to-Grid (V2G) mode (discharging), the power flow is reversed. The stored energy in the EV battery is converted back into AC and injected into the grid. In this case, the same switches operate in an inverter-like manner, where $S_{D1}$and S_{D2}actively control the current direction and waveform. The inductor Lagain plays a key role in smoothing the current and ensuring that the injected current is sinusoidal and synchronized with the grid voltage. This allows the EV to support the grid during peak demand, improve load balancing, and enhance overall grid stability.

Overall, this bidirectional PFC rectifier topology is highly suitable for V2G applications because it ensures efficient energy conversion, reduced harmonic distortion, high power factor, and seamless transition between charging and discharging modes, making it an essential component in modern smart grid and EV infrastructure.

V. CONCLUSION

This survey paper has presented a comprehensive analysis of 5-level bidirectional PFC rectifiers for Vehicle-to-Grid (V2G) applications, highlighting their growing importance in modern electric vehicle and smart grid ecosystems. From the reviewed literature, it is evident that multilevel converter topologies, particularly 5-level configurations, offer significant advantages over conventional two-level systems, including reduced total harmonic distortion (THD), improved power factor, lower switching losses, and enhanced efficiency. The integration of bridgeless structures, switched capacitor techniques, and transformer-less designs further contributes to improved performance, compactness, and cost-effectiveness.

Additionally, various control strategies such as PI, predictive, and intelligent optimization-based methods have been explored to ensure stable bidirectional operation, accurate voltage regulation, and efficient energy transfer between the grid and EV batteries. The studies also emphasize the importance of scalability, modularity, and wide output voltage range to meet the dynamic requirements of EV charging and discharging in V2G systems.

However, despite these advancements, several challenges remain, including increased control complexity, capacitor voltage balancing issues, and the need for robust real-time optimization techniques. Future research should focus on developing simplified control algorithms, integrating renewable energy sources, and applying machine learning techniques to enhance adaptability and system intelligence.

Overall, 5-level bidirectional PFC rectifiers represent a promising and efficient solution for next-generation EV charging infrastructure and V2G applications, offering a balanced trade-off between performance, reliability, and implementation complexity.

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