International Journal of Advanced Research and Multidisciplinary Trends (IJARMT)
An International Open Access, Peer-Reviewed Refereed Journal
Impact Factor: 7.2 Website: https://ijarmt.com ISSN No.: 3048-9458

Review paper on Power Quality of Bidirectional Rectifier for Electric Vehicle Charging System

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ABSTRACT
The rapid growth of electric vehicles (EVs) has significantly increased the demand for efficient and grid-friendly charging infrastructures. Bidirectional rectifiers have emerged as a key technology in EV charging systems, enabling two-way power flow between the vehicle and the grid, commonly referred to as Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations. This bidirectional capability not only enhances energy utilization but also supports grid stability by allowing EVs to function as distributed energy storage systems. However, the integration of bidirectional rectifiers introduces critical power quality challenges, including harmonic distortion, poor power factor, voltage fluctuations, and increased electromagnetic interference. This review paper presents a comprehensive analysis of power quality issues associated with bidirectional rectifiers in EV charging systems. Various rectifier topologies such as PWM-based active front-end converters, multilevel rectifiers, and transformer-less configurations are examined in terms of their impact on total harmonic distortion (THD), efficiency, and power factor improvement. The study also highlights the limitations of conventional unidirectional rectifiers, which suffer from nonlinear behavior and degraded power quality, thereby emphasizing the advantages of active bidirectional designs. Furthermore, the paper reviews advanced control strategies, including power factor correction (PFC), adaptive controllers, and intelligent techniques, aimed at mitigating power quality issues and ensuring compliance with standards such as IEEE 519. The role of bidirectional converters in integrating renewable energy sources and stabilizing distribution networks is also discussed, particularly under high EV penetration scenarios.

Keywords: Electrical Vehicles, Power Quality, Bidirectional Rectifier

1. INTRODUCTION
The increasing global adoption of electric vehicles (EVs) has led to a rapid expansion of charging infrastructure, placing new demands on power electronic converters used in these systems. Among these, bidirectional rectifiers have gained significant attention due to their ability to enable two-way power flow between the utility grid and EV batteries. This capability supports both Grid-to-Vehicle (G2V) charging and Vehicle-to-Grid (V2G) operation, allowing EVs not only to consume energy but also to supply it back to the grid. As a result, bidirectional rectifiers play a vital role in improving energy management, enhancing grid stability, and supporting the integration of renewable energy sources.

Despite these advantages, the use of bidirectional rectifiers introduces several power quality challenges that must be carefully addressed. Power quality refers to the stability and purity of electrical power delivered to loads, and it is often affected by harmonics, reactive power, voltage fluctuations, and electromagnetic interference. In EV charging systems, nonlinear switching behavior of power electronic converters can lead to increased Total Harmonic Distortion (THD), reduced power factor, and disturbances in the distribution network. These issues not only degrade system performance but also violate regulatory standards such as IEEE 519, making power quality improvement a critical aspect of bidirectional rectifier design [1, 2].

Traditional unidirectional rectifiers, such as diode bridge rectifiers, are simple and cost-effective but suffer from poor power factor and high harmonic distortion. In contrast, modern bidirectional rectifiers—particularly those based on Pulse Width Modulation (PWM) and active front-end (AFE) topologies—offer better control over input current shaping and output voltage regulation. Advanced multilevel converter structures further enhance performance by reducing switching losses and improving waveform quality. However, these improvements come at the cost of increased circuit complexity, control requirements, and design challenges [3].

To mitigate power quality issues, various control techniques have been developed, including power factor correction (PFC), hysteresis control, predictive control, and intelligent methods based on artificial intelligence and machine learning. These strategies aim to reduce harmonics, improve efficiency, and maintain stable operation under varying load and grid conditions. Additionally, the integration of bidirectional rectifiers with renewable energy sources, such as solar and wind, introduces further complexity, requiring robust and adaptive control mechanisms [4].

This review paper focuses on analyzing the power quality aspects of bidirectional rectifiers used in EV charging systems. It examines different converter topologies, control strategies, and their impact on key performance parameters such as THD, power factor, efficiency, and voltage regulation. The paper also highlights current challenges, recent advancements, and future research directions aimed at developing high-performance, energy-efficient, and grid-compliant EV charging solutions [5, 6].

2. KEY POWER CONVERTER FEATURES FOR EV CHARGING SYSTEMS

In order to effectively accomodate the specifications/battery voltages of the commercially available EVs and available power source (single- and/or three-phase), while efficiently charging the EV battery and supporting the utility grid, some essential features of the power converters are summarized herewith:

- Power factor: A high power factor near unity is essential for EV charging to maximize energy efficiency, minimize power losses, optimize power grid utilization, and reduce overall electricity consumption and cost.
- Single and three-phase power converters: Single-phase PFC rectifiers are commonly used for onboard EV charging due to their compactness and lightweight design, making them suitable for charging from a standard household outlet. On the other hand, three-phase PFC rectifiers are used for off-board EV charging, as they provide higher power output, making them suitable for fast charging stations with high charging demands [7, 8].
- Bidirectional power flow: A bidirectional power converter is crucial for both G2V charges and V2G discharging processes in EVs. It includes components such as an AC-to-DC converter, DC-to-DC converter, and DC-to-AC inverter. It efficiently manages the bidirectional flow of

electricity, complies with safety standards, and incorporates advanced control algorithms for seamless communication between the EV, the grid, and the converter [9].

- Wide voltage range: EV chargers must provide a wide range of output DC voltage to accommodate different nominal battery voltage levels. To meet this requirement, EV chargers must be designed with efficient and reliable voltage regulation and current control mechanisms, ensuring safe and optimal charging performance for different EVs and batteries.

3. LITERATURE REVIEW

Reddy et al. (2025, [1]), present a fuzzy logic–controlled dual active full bridge (DAFB) converter topology aimed at reducing current ripple in electric vehicle charging applications. The proposed approach utilizes intelligent fuzzy control to regulate power flow and minimize ripple effects, which directly contributes to improved power quality and reduced stress on power electronic components. Although the work demonstrates effective ripple reduction and improved dynamic performance, the topology relies on an isolated dual active bridge structure. The study highlights the importance of advanced control strategies in EV chargers but does not explicitly address transformer-less configurations or grid-side power quality issues such as harmonic distortion and DC injection. This creates a research gap for extending intelligent control techniques to bidirectional transformer-less EV charging systems for grid power quality enhancement.

Chavhan et al. (2024, [2]), provide a comprehensive review of recent advancements and challenges in Battery Energy Storage Systems (BESS), emphasizing their role in renewable integration, electric vehicles, and smart grids. The paper discusses key issues such as power quality, bidirectional power flow, system efficiency, and grid interaction challenges associated with BESS. While the study thoroughly analyzes storage technologies and system-level concerns, it lacks a focused discussion on power electronic interfaces, particularly transformer-less bidirectional EV chargers and their impact on grid power quality. The review underscores the growing need for efficient bidirectional converters with improved power factor and harmonic mitigation, thereby motivating further research into grid-connected transformer-less EV charging systems.

Allu Bhargav et al. (2023, [3]), an analysis of a PV-based isolated-bidirectional electric vehicle charger (IBEVC) for household use is presented in this work to charge EV batteries while simultaneously improving power quality. When adequate PV power is free, the electrical power produced by PV is utilized to charge EV batteries, private loads, and feed capacity to the utility framework in this IBEVC framework. The EV battery and IBEVC provide reactive power when PV power is insufficient, and the grid supplies active power to household appliances. The fundamental load current is extracted using the Logarithmic hyperbolic cosine (LHC) based algorithm for IBEVC's harmonic compensation. The Dual active bridge (DAB) converter is used to isolate the battery from the supply for bidirectional power flow to the battery for charging and discharging. Extended phase shift (EPS) modulation is used to boost the DAB's efficiency and reduce inductor current and device current stress. In-depth discussion is given to the IBEVC's various charging and discharging modes and power quality enhancement capabilities.

Rajesh Kumar Lenka et al. (2022, [4]), introduces solar power generation (PV) with a lattice integrated multifunctional bi-directional off-board battery charger (EVBC). This loads the EV battery and simultaneously improves the electrical quality of power grid performance (PQ). EVBC is very undressed, so there are two modes of operation: operating. H. Grill Connection Mode

(GCM) and Island Mode (IM). In GCM, the EVBC controller promotes EV load/load and improves the points of common coupling voltage (PCC) and grid current PQ. To this end, sinus-type reference currents are generated using the active electrical component (ACC) of the load current and the synchronous voltage template (SVT) estimated from the grid borat. This paper proposes a control technique (self-adjusted filter) for extracting ACC and SVT from load current or main voltage. The EVBC controller maintains the energy balance of the IMS by charging/unloading the EV battery depending on the availability of PV performance. Additionally, EVBC ensures uninterrupted care with raw loading by maintaining the pure sinus voltage of the PCC. Additionally, the EVBC controller takes over STF-based phase error-minimization technology to maintain a seamless transition from IN's GCM. The EVBC simulation model is developed by Matlab-Simulink, and the proposed STF-based control technology is implemented. Hospitalization and temporary performance of EVBC using the proposed control technique has been validated with GCM and IM operations.

Nikitha Paidimukkala et al. (2022, [5]), this research activity is mainly on the integration of photovoltaic smart grid (PV) and electric vehicles (EVs) with bidirectional power flow capability by charging/discharging using power converters and power quality improvement. Due to the increasing energy demand due to the rapid population growth, there is a need to modernize the power grid by improving the power quality so that the energy converted by photovoltaic photovoltaics (SPVs) can be transmitted and stored in batteries as surplus power that can be used during peak demand. EV batteries are charged during low demand and discharged during peak demand. EVs act as both loads and energy suppliers for SG. Simulation results demonstrate the operation of the networked intelligent G2V system by observing and improving factors such as power factor, power control, and harmonic elimination by using MATLAB/Simulink software to build a power electronics network that can perform bidirectional power flow and balance the network. Then, the improvement of power quality of the integrated system is studied in detail by analyzing the power compensation, voltage regulation and harmonic mitigation of the integrated system.

M. Safayatullah et al. (2022, [6], wide-scale reception and extended development of electric vehicles (EVs) require innovative work of force electronic converters to accomplish high power, minimal expense, and solid charging answers for the EV battery. This paper presents an extensive survey of EV off-board chargers that comprise of ac-dc and dc power stages from the power organization to the EV battery. Although there are two types of EV chargers, on-board and off-board, it is essential to use off-board chargers for dc fast and ultra-fast charging in order to significantly reduce the volume and weight of the EV. The most recent topologies and control strategies for ac-dc and dc-dc power stages for off-board chargers are discussed here, with a focus on technical details, ongoing progress, and challenges. Also, the vast majority of the new multiport EV chargers coordinating PV, energy capacity, EV, and matrix are introduced. Also, similar examination has been completed for the geographies and the control plans of ac-dc rectifiers, dc converters, and multiport converters as far as design, power and voltage levels, proficiency, bidirectionality, control factors, benefits, and impediments which can be utilized as a rule for future exploration headings in EV charging arrangements.

R. K. Lenka et al. (2021, [7]), investigates the software of a vehicle-to-grid (V2G)-enabled bidirectional off-board electric powered vehicle (EV) battery charger at the grid cutting-edge harmonic compensation (GCHC) and reactive electricity compensation (RPC) and concurrently makes use of it as a battery charger and electricity generator. To generate reference cutting-edge, the proposed EV charger manage set of rules processed the nonlinear residential load cutting-edge and factor of not unusualplace coupling (PCC) voltage, to estimate the lively load cutting-edge aspect and synchronizing voltage template, respectively. The EV charger manage set of rules makes use of an adaptive notch clear out out (ANF) to generate the in-section and 90° shifted synchronizing voltage template from PCC voltage. Furthermore, a resonant clear out out is used to extract the essential frequency residential load cutting-edge aspect accurately. The extracted essential aspect is sampled and keep at 0 crossings of the 90° shifted synchronizing voltage template to estimate the lively load cutting-edge aspect. As a result, the proposed manage set of rules guarantees powerful overall performance without relying on any section-locked loop (PLL). The charger overall performance with the proposed manage set of rules is demonstrated with the aid of using the simulation outcomes acquired the usage of MATLAB/Simulink. Furthermore, an off-board EV battery charger experimental prototype is constructed withinside the laboratory to confirm the acquired simulation outcomes.

4. BIDIRECTIONAL RECTIFIER

A bidirectional rectifier is a power electronic converter that enables the flow of electrical energy in both directions between the AC grid and a DC load, such as an electric vehicle (EV) battery. Unlike conventional unidirectional rectifiers, which only convert AC to DC, bidirectional rectifiers support both rectification (AC to DC) and inversion (DC to AC). This dual functionality is essential for modern EV charging systems, particularly in applications involving Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations.

In G2V mode, the bidirectional rectifier operates as a rectifier, converting AC power from the grid into DC power to charge the EV battery. During this process, it ensures controlled charging with improved power factor and reduced harmonic distortion. In V2G mode, the converter functions as an inverter, allowing stored energy in the EV battery to be fed back into the grid. This capability supports grid stabilization, peak load management, and efficient utilization of distributed energy resources.

The most commonly used topology for bidirectional rectifiers is the Pulse Width Modulation (PWM)-based Voltage Source Converter (VSC), typically implemented using Insulated Gate Bipolar Transistors (IGBTs) or MOSFETs. These converters allow precise control of input current and output voltage, enabling near-unity power factor and low Total Harmonic Distortion (THD). In addition, multilevel converter topologies, such as Neutral Point Clamped (NPC) and Cascaded H-Bridge (CHB), are increasingly being used to further enhance waveform quality and reduce switching losses.

Despite their advantages, bidirectional rectifiers present several challenges. The switching actions of power semiconductor devices introduce harmonics into the system, which can degrade power quality if not properly controlled. Additionally, the design of efficient control algorithms is crucial to ensure stable operation under varying load and grid conditions. Issues such as electromagnetic interference (EMI), increased system complexity, and higher implementation costs must also be considered.

To address these challenges, advanced control techniques such as power factor correction (PFC), hysteresis current control, and model predictive control are widely employed. These methods help in shaping the input current, minimizing harmonics, and maintaining voltage regulation. Moreover, digital controllers and intelligent algorithms are increasingly being integrated to improve adaptability and performance in dynamic environments.

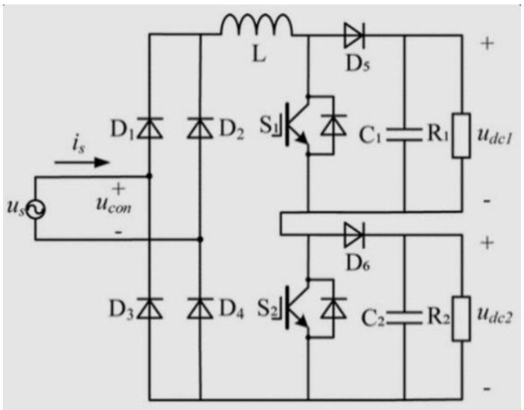

Figure 1: Bidirectional Rectifier

5. CONCLUSION

Bidirectional rectifiers have become a fundamental component in modern electric vehicle (EV) charging systems due to their ability to facilitate two-way power flow and support advanced functionalities such as Vehicle-to-Grid (V2G) operation. This review has highlighted that, while bidirectional rectifiers significantly enhance energy efficiency, grid interaction, and renewable energy integration, they also introduce notable power quality challenges that must be effectively addressed.

The study examined various rectifier topologies, including PWM-based active front-end converters and multilevel structures, which offer improved performance in terms of Total Harmonic Distortion (THD), power factor, and efficiency compared to conventional unidirectional rectifiers. However, these advanced designs often increase system complexity and require sophisticated control mechanisms. Power quality issues such as harmonics, voltage fluctuations, and electromagnetic interference remain critical concerns, particularly under high EV penetration and dynamic operating conditions.

Furthermore, the review emphasized the importance of advanced control strategies, including power factor correction (PFC), predictive control, and intelligent techniques, in mitigating these challenges. These methods play a crucial role in ensuring compliance with grid standards, enhancing system stability, and optimizing overall performance. The integration of renewable energy sources with EV charging infrastructure further underscores the need for robust and adaptive bidirectional rectifier designs.

In conclusion, achieving high power quality in bidirectional rectifiers requires a balanced approach that considers efficiency, complexity, cost, and reliability. Future research should focus on developing simplified control algorithms, reducing harmonic distortion, improving converter efficiency, and designing compact and cost-effective solutions. With continued advancements in power electronics and control techniques, bidirectional rectifiers are expected to play a key role in enabling sustainable, intelligent, and grid-friendly EV charging systems.

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