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Design of Grid Connected Wireless Power Transfer Technologies: A Comprehensive Review

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Abstract –*Wireless Power Transfer (WPT) technology has emerged as a promising solution for electric vehicle (EV) battery charging, eliminating the need for physical connectors and improving user convenience. Recently, Bidirectional Wireless Power Transfer (BD-WPT) systems have gained significant attention due to their ability to not only charge EV batteries but also feed energy back to the grid, supporting grid stability and energy efficiency. This paper provides a comprehensive review of BD-WPT systems, focusing on their integration with the power grid, controller design strategies, and approaches for ensuring Unity Power Factor (UPF) at the grid side. Detailed mathematical modeling of system components is discussed, along with an overview of control techniques employed for optimal bidirectional power flow. The review further explores the impacts of large-scale EV integration on grid stability and presents key simulation studies validating theoretical concepts, particularly in MATLAB/Simulink environments. Future research directions and challenges in implementing efficient, stable, and safe BD-WPT systems are also highlighted.*

Keywords - ***Bidirectional Wireless Power Transfer (BD-WPT), Electric Vehicles (EV), Grid Integration, Unity Power Factor (UPF), Controller Design, MATLAB, Simulink.***

I- INTRODUCTION

The global shift towards sustainable transportation has led to a rapid rise in the adoption of electric vehicles (EVs). Driven by concerns over environmental pollution, depleting fossil fuel reserves, and governmental policies promoting clean energy solutions, EVs are fast becoming an integral part of modern transportation systems. However, the increased penetration of EVs also brings forth new challenges, particularly in terms of charging infrastructure, grid stability, and power management. Conventional plug-in charging systems for EVs require physical connectors, which not only pose limitations related to mechanical wear and tear, user convenience, and safety but also restrict the potential for dynamic or automated charging processes. To overcome these challenges, Wireless Power Transfer (WPT) technology has gained significant attention. WPT eliminates the need for physical contact by using electromagnetic fields to transfer power wirelessly, offering advantages such as improved user convenience, reduced maintenance, and the ability to implement dynamic charging scenarios (e.g., charging while driving).

While unidirectional WPT systems have been extensively studied and implemented for EV battery charging, there has been growing interest in the concept of Bidirectional Wireless Power Transfer (BD-WPT). BD-WPT systems enable two-way power flow: they not only allow energy transfer from the grid to the EV battery (Grid-to-Vehicle, G2V) but also facilitate energy feedback from the EV battery to the grid (Vehicle-to-Grid, V2G). This bidirectional capability opens up new possibilities for utilizing EVs as distributed energy resources (DERs), contributing to grid stabilization, peak load shaving, frequency regulation, and renewable energy integration.

However, integrating a large number of EVs with BD-WPT capabilities into the power grid introduces several technical challenges. One of the key concerns is maintaining high power quality and ensuring Unity Power Factor (UPF) at the grid side. Poor power factor operation leads to inefficient energy usage, increased losses, and voltage regulation issues within the grid. Therefore, achieving UPF control during both charging and discharging operations is essential to ensure efficient and stable grid operation.

This paper presents a detailed review of BD-WPT systems focusing on their role in EV battery charging and grid interaction. It highlights the fundamental principles, system architecture, and mathematical modeling of key components such as grid-side and vehicle-side converters, compensation networks, and coupling mechanisms. Special emphasis is placed on controller design strategies to regulate bidirectional power transfer while achieving UPF at the grid interface. The control techniques discussed include Proportional-Integral (PI) controllers, synchronous reference frame-based controllers, and advanced modulation schemes.

Moreover, the paper examines the impact of large-scale EV integration on the power grid, addressing concerns such as grid congestion, voltage instability, harmonic distortion, and load variability. Solutions involving smart grid technologies, demand response strategies, and vehicle aggregators are also explored.

To validate the analytical concepts and control methodologies, various simulation studies conducted using MATLAB/Simulink are reviewed.

In summary, this review aims to provide a comprehensive understanding of the current state, challenges, and future directions of BD-WPT systems for EVs, particularly emphasizing grid integration with efficient control strategies for optimal performance.

II-BIDIRECTIONAL TOPOLOGY

BIDIRECTIONAL DC–DC CONVERTERS:

In principle, bidirectional power transfer among the two unipolar DC voltage sources may be established with the two unidirectional DC–DC converters i.e. C1

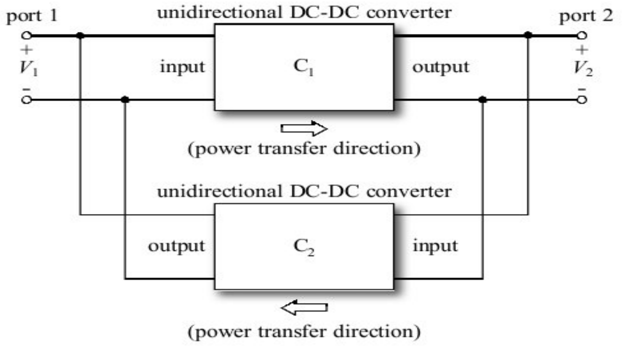

Fig 1Principle construction of a bidirectional DC-DC converter using two unidirectional DC-DC converters.

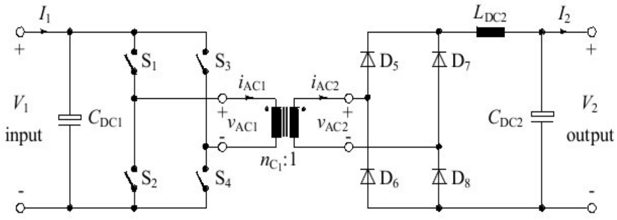

Fig 2 Unidirectional full bridge DC–DC converter with output inductor LDC2

The converters C1 and C2 in Fig 1. can be replaced by using the depicted unidirectional full bridge converter, however, for converter C2, the indices 1 and 2 need to be interchanged.

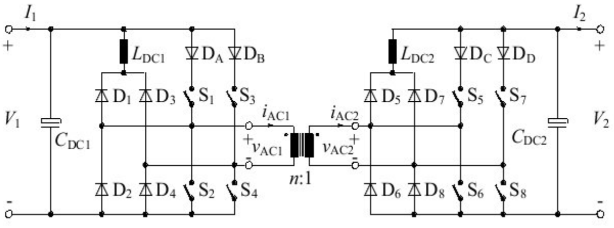

Fig 3. Bidirectional full bridge DC–DC converter topology

This is constructed using two unidirectional full bridge DC–DC converters C1 and C2 converters according to Fig 1 and Fig 3 the diodes DA, DB, DC, and DD are required in order for avoiding reverse blocking voltages across S1-S8 and C2 according to Fig 1. Therefore, C1 is used for power transferring from port 1 to port 2 (forward direction and forward operating mode) and C2 converter is required to transfer power in the opposite direction (backward direction, backward operating mode). In order for an illustration an example of a practical converter realization using galvanic isolation, full bridge DC–DC converters along with high frequency (HF) transformers and output inductors are employed for C1 and C2 converters.

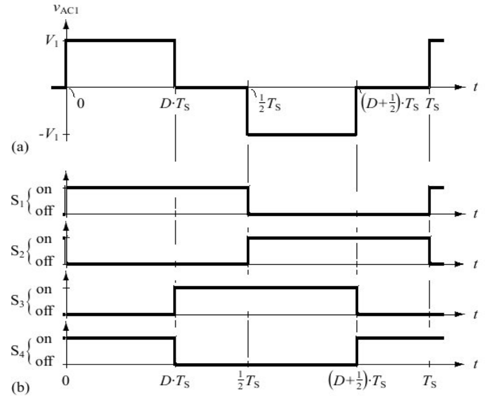

Fig 4 (a) Transformer voltage VAC1(t) generated with the inverter stage on DC-DC converter depicted in Fig 2 and Fig 3; (b) Respective switching states of S1,S2,S3 and S4

For the clarity purposed, the full bridge DC–DC converters C1 and C2 are considered to be lossless and without any parasitic inductive and capacitive components. Additionally, a huge smoothing inductor (Fig 2) are considered and hence its characterization of the system functionality confines to the rectifiers.

In forward mode of operation, i.e. power is transferred among the port 1 to port 2 (Fig 1), the converter C1 is basically active and its inverter stage applies an rectangular AC voltage VAC1(t) along with a constant frequency f_s=1/TS and its arbitrary duty cycle $0 < D < 0.5$ to the winding of primary of the HF transformer (Fig 4).Basically, in Fig 4 represents the pulse generation pattern whereas V_AC1 is representing the applied voltage and whereas other four waves are representing the switching state across S1,S2,S3,S4 respectively and the duty cycle are kept 50% of the switching pulses. The (ideal) HF transformer usually just alters the amplitude of AC voltage according to its turns ratio nC1, i.e.V_AC2 (t)=(V_AC2 (t))/(nC_1), and applies V_AC2 (t) to the side of the rectifier. By using the assumption of ideal low-pass filtering and concept of continuous conduction mode of operation, the rectified output voltage V2 is obtained.

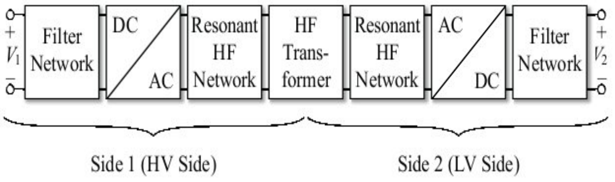

Fig 5 The different components required for an isolated, bidirectional DC-DC converter.

The various components of a bidirectional DC–DC converter along with the galvanic isolation are depicted in Fig 5In the port 1 and port 2 the filter networks provided for smoothing the terminal voltages and currents. For each filter networks, at least a single inductor or a single capacitor is employed.

The DC–AC converter is nothing but a network switch which provides AC power to the HF transformer and the AC–DC converter supplies the DC power for the receiving port; both these converters must be allowed for bidirectional power transfer. Typically, a full bridge circuits, half bridge circuits, and push-pull circuits are employed for this operation. However, for different solutions e.g. the single switch networks used in a bidirectional flyback converters are required. The reactive HF networks generally provides energy storage capability within the HF AC part and are also used for modifying the shapes of the current switch waveforms in order to achieve a lower switching loss. Although, these parts are not necessarily required for a fully functionally bidirectional DC–DC converter, they will always be present in the practice due to the parasitic components of the HF transformer for e.g. stray and magnetizing inductances, parasitic capacitances

The HF transformer is required in order to achieve electric isolation; it is further enables a large voltage and current transfer ratios between them. The HF transformer is basically considered as a superior over a low frequency transformer, since the transformer and its filter components become smaller (and often less expensive) at higher frequencies Bidirectional DC–DC converter topologies along with a system configuration according to Fig 5, are called as a Single-Stage Topologies, since they generally contain a minimum number of conversion stages. Accordingly, to the total number of components required it is comparably low. However, the operation along the wide input and output voltage ranges causes ineffective transformer and switch utilization. Improved transformers and switch utilization are achieved using multi-stage topologies, which normally contains some additional power converters to adjust current and voltage levels.

III - APPLICATIONS

E**lectric Vehicle (EV) Battery Charging:** Enables contactless charging at homes, public stations, or workplaces. Both stationary and dynamic (on-the-move) charging are possible.

Vehicle-to-Grid (V2G) Operations: EVs act as distributed energy storage units. Power can be fed back to the grid during peak demand periods.

Renewable Energy Integration: EVs with BD-WPT can store excess power generated from solar or wind sources and discharge back to the grid when needed.

Micro grid and Smart Grid Applications: BD-WPT-enabled EVs contribute to frequency regulation, voltage stabilization, and demand response services in micro grids.

Public Transport Fleets: Electric buses and taxis equipped with BD-WPT technology can charge wirelessly at depots and return excess energy during idle periods.

IV - CHALLANGES

Efficiency Losses: Power transfer efficiency drops with coil misalignment, increased air gap, and high frequency switching losses.

High Implementation Cost: Initial costs of BD-WPT hardware, control systems, and infrastructure setup are substantial.

Electromagnetic Interference (EMI) & Safety Concerns: Strong magnetic fields may interfere with nearby electronics and pose health/safety issues.

Standardization Issues: Lack of unified global standards for BD-WPT system designs, communication protocols, and interoperability.

Grid Impact & Stability: High penetration of bidirectional EVs may lead to voltage fluctuations, reverse power flow issues, and harmonics in the grid.

Complex Control Requirements: Requires sophisticated real-time control systems to manage bidirectional flow, grid synchronization, and UPF.

Cyber security: Communication links between grid, EVs, and control centers are susceptible to cyber attacks.

V - CONCLUSION

The rapid transition towards electrified transportation systems and the growing emphasis on smart grids necessitate innovative and efficient energy transfer technologies. Bidirectional Wireless Power Transfer (BD-WPT) systems for Electric Vehicles (EVs) present a promising solution to address the challenges associated with conventional plug-in charging methods and offer added flexibility through Vehicle-to-Grid (V2G) functionality.

This review paper has comprehensively analyzed the architecture, mathematical modeling, control strategies, and grid integration aspects of BD-WPT systems. Special attention has been given to the design of controllers that regulate bidirectional power flow while maintaining Unity Power Factor (UPF) at the grid interface—critical for grid stability and efficient energy usage. Additionally, simulation results validate the effectiveness of the control methodologies and system design in ensuring smooth bidirectional energy transfer, maintaining power quality, and achieving desired battery charging/discharging objectives.

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