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EXPLORING THE POTENTIAL OF BI-DIRECTIONAL POWER CONVERTERS IN V2G ELECTRIC VEHICLE SYSTEMS: A COMPREHENSIVE SURVEY

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Abstract

The number of electric vehicles (EVs) on the road has increased considerably in recent years due to the rapid development of EV technology. This surge in EV adoption has led to an increased demand for effective Vehicle-to-Grid (V2G) systems that can enable Bi-Directional Power-Flow (BDPF) between EVs and the grid. Bi-directional Power Converters (BPC) play a crucial role in facilitating this bi-directional energy transfer, ensuring efficient power management and enhancing the overall performance of V2G systems. This work aims to explore the potential of various bi-directional power converters, including Bi-directional DC-DC Converters (BDC), Resonant-Converters (RC), Multi-Level Inverters (MLI), Bi-directional-Resonant Converters (BRC), Multi-Level Bi-directional DC-DC converters (MLBDC), Multi-Level-Converters (MLC), and Multi-Level Bi-directional Resonant-Converters (MLBRC), in V2G electric vehicle systems. The literature survey reveals the advantages and challenges associated with each type of converter.

Keywords: Electric Vehicle, Vehicle-to-Grid, Bi-directional Converters, Multi-Level Inverters.

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1 Introduction

Electric cars, also known as EVs are automobiles that get their propulsion through a variety of electric motors and get their electrical power either from batteries that can be recharged or by using an external power source. Over the past few years, EVs have attracted a lot of attention and acquired a lot of popularity mainly because they can decrease emissions of greenhouse gases and reduce their reliance on fossil fuels [1]. Plug-in hybrid EVs (PHEVs), as well as Battery EVs (BEVs), are the two most common EV variants. BEVs are powered solely by electricity and rely on rechargeable batteries for energy storage. The EVs don't have an Internal-Combustion-Engine (ICE), so they don't make any pollution out of their tailpipes. BEVs offer a range of driving distances that vary depending on the battery capacity and vehicle efficiency. They need to be charged using electric charging stations or home charging units. Hybrid electric vehicles (PHEVs) have an internal combustion engine (ICE), battery pack, as well as electric motor. [2]. There's a limited range in which they can run only on electricity before switching to ICE. PHEVs offer the flexibility of running on electric power or switching to the combustion engine for longer trips, providing greater range compared to BEVs [3].

Power converters also known as Power-Electronic Converters (PECs) are electrical circuits that convert one form of electrical power to another. They're essential in a wide range of uses, from televisions and computers to manufacturing equipment to electric automobiles [4]. PECs enable the efficient control and transformation of electrical energy, allowing it to be adapted to different voltage levels, frequencies and waveforms as required by the specific application. The primary function of a PEC is to convert electrical energy from a source with certain characteristics (input) to a desired output with different voltage, current or waveform characteristics. This conversion is achieved through the use of power semiconductor devices such as diodes, transistors and thyristors. To generate the desired output, PECs switch the semiconductor devices on and off quickly to regulate the flow of current and voltage [5].

There are several types of power converters, each designed for specific applications. Some of the converters include AC-DC Converters [6], DC-AC Converters [7], DC-DC Converters [8], AC-AC Converters [9] and BPC [10]. AC-DC Converters (Rectifiers) convert Alternating-Current (AC) to Direct-Current (DC). They are commonly used in power supplies for electronic devices, where a stable and regulated DC voltage is required. DC-AC Converters (Inverters) convert DC to AC. They are widely used in applications such as solar power systems, Uninterruptible Power-Supplies (UPS) and EV inverters to convert DC power from batteries or renewable sources to AC power for use in various devices and equipment. DC-DC Converters convert DC voltage from one level to another. They are used in a wide range of applications, including voltage regulation, energy storage systems and power distribution in electronic devices. AC-AC converters are used to convert AC power from one voltage level to another while maintaining the AC waveform. They are employed in applications such as voltage regulation, frequency conversion and power-grid interconnections. BPC allow the flow of power in both directions, enabling bi-directional energy transfer between different energy sources or storage systems. They are essential components in applications like electric vehicle charging stations and V2G systems. PECs also require control systems to ensure the proper operation of the conversion process. Control techniques such as Pulse-Width-Modulation (PWM) and feedback loops are used to regulate the output voltage, current and other parameters, ensuring stable and efficient operation. Power-Electronic-Converters (PECs) are shown in their renewable energy system uses in Figure 1 [11].

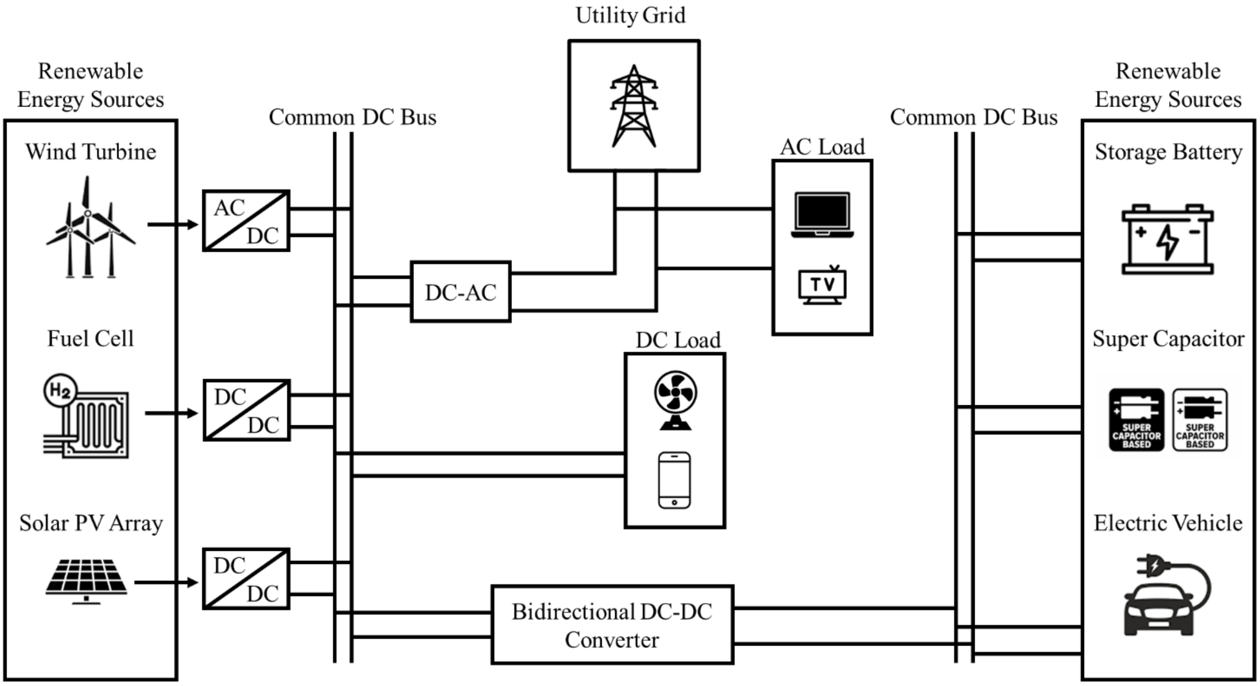

Figure 1. Enhancing Renewable Energy Systems with Power Electronic Converters. [11]

The term V2G" represents the two-way transfer of energy among EVs as well as the Power-Grid. With V2G technology, electric vehicles can become mobile energy storage units that can both draw power from and contribute to the grid [12]. The potential of bi-directional power converters in V2G systems is significant. The integration of EVs with V2G systems holds great promise for the future of sustainable energy. BPC play a crucial role in enabling efficient energy exchange between EVs and the grid in V2G systems. The utilization of BPCs allows EVs to not only consume energy from the grid but also to supply unused energy back to the grid during a shortfall. This bi-directional energy flow opens up a range of opportunities and advantages. Firstly, it enables demand response capabilities, where EVs can adjust their charging and discharging patterns to support grid stability and respond to fluctuating electricity demand. This flexibility allows EVs to act as distributed energy resources, contributing to load balancing and reducing the power supply risks by shaving the peak demand and transferring the shaved amount in off-peak periods. Secondly, BPCs facilitate the integration of renewable energy sources into the grid. EVs can store excess energy from renewable sources during periods of high generation and release it during times of increased demand or low renewable energy availability. This enhances grid reliability, reduces curtailment of renewable energy and supports the integration of intermittent renewable resources. Furthermore, the deployment of BPCs in V2G systems opens up opportunities for necessary services. EVs can provide valuable grid services such as frequency regulation and voltage support through their bi-directional energy flow capabilities. By participating in necessary service markets, EVs can contribute to grid stability and reliability while potentially generating revenue for EV owners. However, there are challenges to be addressed for the widespread adoption of BPCs in V2G systems. These challenges include standardization of communication protocols, inter-operability, grid-infrastructure readiness and managing the impact on battery life and degradation [13]. Additionally, economic viability and regulatory frameworks need to be considered to incentivize the participation of EV owners in V2G programs [14].

1.1 Background and Motivation

The background and motivation for exploring the potential of BPCs in V2G electric vehicle systems stem from the increasing need to address the challenges associated with integrating electric vehicles into the existing power grid infrastructure. EVs have gained considerable popularity as an environmentally friendly alternative to traditional ICE vehicles. They offer numerous advantages, including lower emissions, reduced dependence on fossil fuels, and the potential for utilizing renewable energy sources. However, the widespread adoption of EVs presents new challenges for the power grid. The charging patterns of EVs are often unpredictable and intermittent, leading to significant variations in energy demand. This variability can strain the grid during peak charging periods and create imbalances in electricity supply and demand.

To overcome these challenges, V2G systems have emerged as a viable solution. V2G technology allows electric vehicles to not only consume energy from the grid but also serve as mobile energy storage units that can inject unused energy back into the grid when needed. This Bi-directional Power-Flow (BPF) capability enables electric vehicles to contribute to grid stability, support peak demand periods, and effectively utilize renewable energy sources. The efficient implementation of V2G systems relies heavily on the integration of BPCs. These converters act as the interface between the EVs battery and the power grid, facilitating the bi-directional flow of energy. They play a crucial role in managing power flow, converting DC power from the BEVs to AC power for grid integration and vice versa. An electric vehicle's power system consists of the battery charger, the powertrain and the regenerative braking system. Figure 2 is a block schematic of the electrical components of a common EV [15].

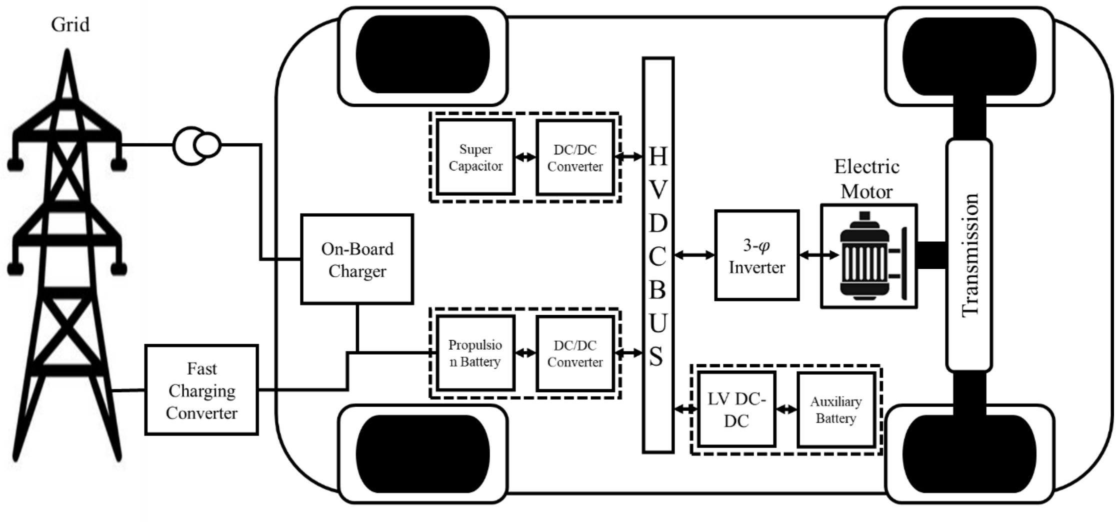

Figure 2. A simplified representation of a rapid-charge station network for electric vehicles [15]

The motivation behind exploring various types of bi-directional power converters, such as BDC, RC, MLI, BRC, MLBDC, MLC and MLBRC, lies in their potential to enhance the performance, efficiency and reliability of V2G systems. These converters offer unique advantages that contribute to efficient power management in V2G systems. BDC for instance, provide a flexible interface between the EVs high-voltage DC bus and the grid allowing precise control of power flow. RC on the other hand, enables soft-switching, reducing power losses and improving overall system efficiency. MLI offer higher power transfer capability and improved grid compatibility by generating high-quality output waveforms with reduced harmonic distortion. BRC combine BPF control with soft-switching characteristics, enhancing system efficiency and reducing switching losses.

The integration of MLBDCs enables handling high power levels with improved voltage-conversion efficiency making them suitable for V2G applications. MLCs in general, provide efficient power transfer and high-power quality minimizing conversion losses and enhancing grid stability. MLBRCs combine the benefits of MLCs and BRCs offering high-power capabilities, improved efficiency and reduced switching losses. Their integration in V2G systems ensures efficient power exchange while maintaining power quality and minimizing power losses. In conclusion, the background and motivation for exploring the potential of BPCs in V2G-EV systems stem from the need to address the challenges associated with integrating EVs into the power grid. By leveraging the capabilities of these converters, V2G systems can effectively manage BPF, optimize energy utilization, enhance grid stability and facilitate the integration of renewable energy sources. Continued research and development in this field are essential for unlocking the full potential of V2G systems and advancing the transition to a sustainable energy future.

2 Literature Survey

Through this paper's literature analysis, we hope to offer a thorough examination of the studies and innovations that have been conducted so far on the subject of BPCs' possible applications in V2G-EV systems. The survey focuses on BDC, RCs, MLIs, BRCs, MLBDCs, MLCs and MLBRCs. The literature survey begins by exploring studies that investigate the integration of BDCs in V2G systems. These studies analyze the design, control and performance aspects of BDCs highlighting their role in efficient power-flow control between EVs and the grid. Next, the survey examines research on RCs in the context of V2G systems. These studies investigate the benefits of RCs, such as reduced switching losses and improved efficiency in facilitating BPF control and enhancing overall system performance. Furthermore, the survey delves into the utilization of MLIs in V2G applications. These studies focus on the advantages of MLIs in achieving high-quality output waveforms with reduced harmonic distortion thereby improving power transfer capability and grid compatibility in V2G systems. The survey then explores research on BRCs and their potential in V2G-EV vehicle systems. These studies investigate the combination of BPF control and soft-switching characteristics offered by RCs highlighting their ability to enhance power transfer efficiency and reduce switching losses.

Additionally, the literature survey covers investigations into MLBDCs and their applicability in V2G systems. These studies analyze the design considerations, control strategies and performance evaluations of MLBDCs emphasizing their capacity to handle high power levels and improve voltage conversion efficiency. Furthermore, the survey examines research on MLCs and their implications for V2G systems. These studies investigate the advantages of MLCs in terms of efficient power management, reduced conversion losses and enhanced grid stability in BPF applications. Lastly, the survey explores studies that investigate MLBRCs and their potential in V2G-EV systems. These studies focus on the combined benefits of MLCs and BRCs, highlighting their ability to provide high-power capabilities, improved efficiency and reduced switching losses in V2G applications. Overall, the literature survey section provides a comprehensive overview of the existing body of knowledge regarding the potential of BPCs in V2G-EV systems. The survey synthesizes research findings and highlights key advancements in BDCs, RCs, MLI, BRCs, MLBDCs, MLCs and MLBRCs. These insights form the foundation for further exploration and analysis in this paper. The taxonomy of the DC-DC converters is given in Figure 3.

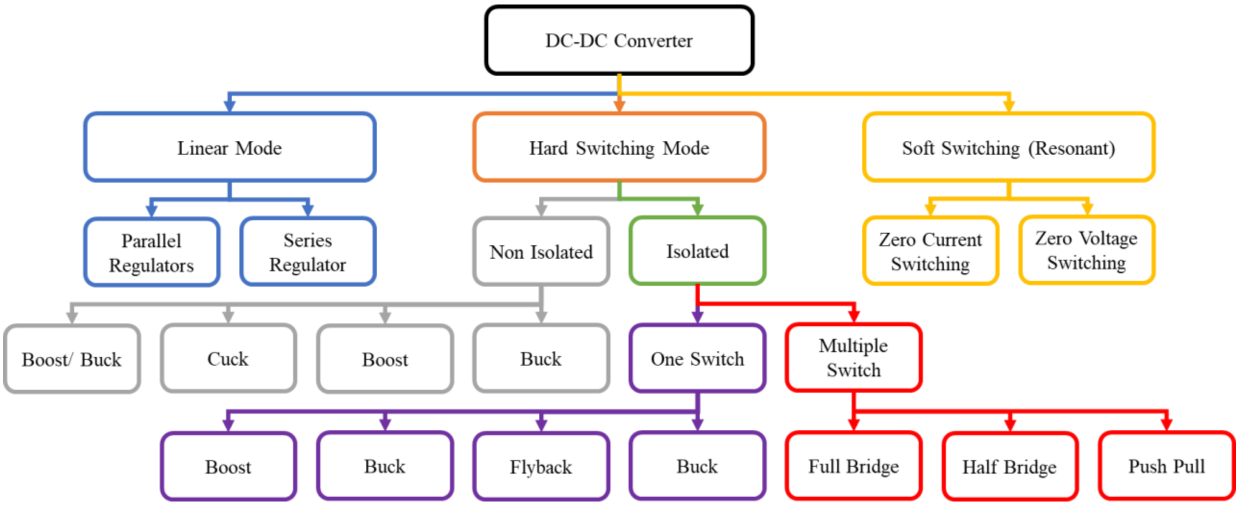

Figure 3. Taxonomy of DC-DC Converter.

2.1 Bidirectional DC-DC Converters (BDCs)

BDCs are widely used in V2G systems to efficiently transfer power between the vehicle's battery and the grid. These converters provide a flexible interface between the high-voltage DC bus of the EV and the grid, allowing for effective power-flow control. By employing bidirectional DC-DC converters, the energy stored in the EV's battery can be utilized for grid support during peak demand periods, while excess power from renewable sources can be seamlessly integrated into the vehicle's battery. The taxonomy of the BDCs has been given in Figure 4.

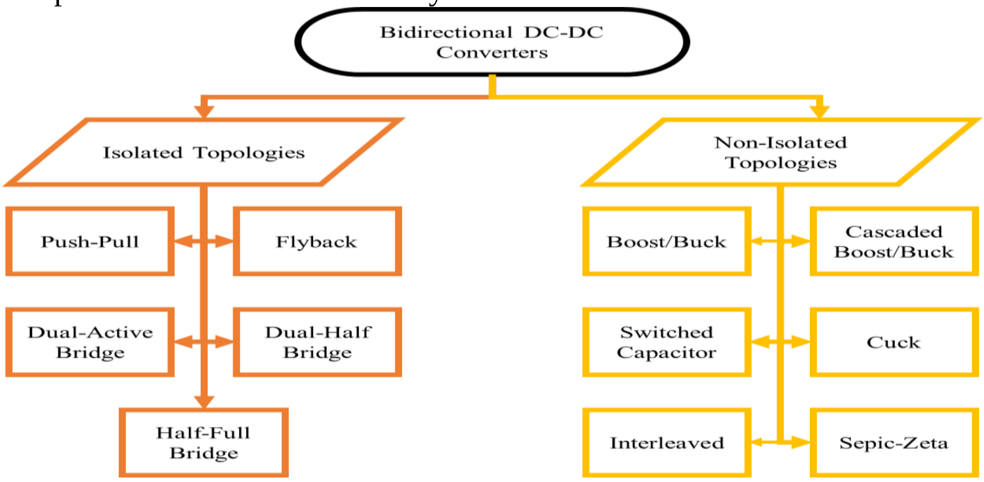

Figure 4: Taxonomy of BDCs.

Recently, there has been a lot of interest in Isolated BDCs due to their potential to prevent power loss because of galvanic separation among the electric vehicle as well as the grid. In addition, non-isolated BDCs have also seen a rise in popularity in recent times as a result of their small physical factor, high efficiency and low cost. In [16], both transformer-based isolated BDCs and impedance-based non-isolated BDCs are reviewed along with the current state of their respective research. Moreover, a framework for assessing BDC topology for the hybrid energy-storage systems is built serving as a useful resource for the subsequent design of such converters. By utilizing the presented framework, they were able to undertake an in-depth analysis of the efficiency of 9 common non-isolated converters in addition to 7 common isolated converters. This paper addresses the challenges of DC-DC converters in hybrid energy-storage systems and makes recommendations to improve future DC-DC converter studies. In [17], authors have presented a survey on the BDC topologies where authors have investigated various operational modes of the BDCs. Further, the authors have presented a converter which can be used in the hybrid EVs. Two modes of operation, Energy-Regenerating High-Voltage DC-Link-Mode and Dual-Source Low-Voltage Powering-Mode have been used with the proposed BDC for attaining the BPF. For handling the electricity flow, this model uses 2 low-voltage sources. For evaluating the model, the authors have used the MATLAB simulator and results show that the presented model has attained better results. The results show that it achieved the maximal energy capacity of 97%. In [18], a non-intrusive method has been presented for the BDC for usage in hybrid EVs. In this model, a black-box detection method has been used for finding the input and output terminals. A Long-Short Term-Memory Neural Network (LSTM-NN) has been presented in this work. Three standard black-box modelling approaches for power converters have been compared with the presented method, demonstrating the improved performance of the presented method. The advantage of the presented method is that it can replicate the behavioural pattern of the BDC. In [19], authors presented a three-phase bi-directional grid-connected AC/DC converter for the V2G-EVs. The main aim of this work is to attain the best BPF amongst the grid and EVs and to smoothen the fluctuation in the power grid. First, the authors presented the settings for the V2F and then presented a mathematical model for the AC/DC converter. A feed-forward decoupling method has been used for the bi-directional AC/DC converter. Finally, for analysis, a Proportional-Integral-Derivative (PID) controlling method has been designed. Authors have evaluated their work on the MATLAB simulator and got better results in comparison with the existing works. In [20], the authors have presented a survey on the BDC topologies which have been utilized in the previous works for the V2G-EVs. The main aim of this survey was to reduce the cost of charging EVs. In this survey, only two conversion methods, DC-DC and AC-DC have been mainly focused. After a complete review, the authors have concluded that a BDC can be designed for providing better BPF among the V2G and Grid-to-Vehicle (G2V) efficiently.

2.2 Resonant DC-DC Converters (RDC)

RDCs are a type of power electronic converters that utilize resonant components such as inductors and capacitors to enable efficient and high-frequency power conversion in V2G-EV systems. These converters offer several advantages, including high efficiency, reduced switching losses and improved power quality, making them well-suited for V2G applications. The basic principle of RDCs involves the use of resonant circuits that create zero-voltage or zero-current switching conditions thereby minimizing power losses during the switching transitions. This is achieved by exploiting the energy stored in the resonant components and allowing the converter to operate at high frequencies which leads to smaller size and weight compared to conventional DC-DC converters. In V2G-EV systems RDCs play a crucial role in facilitating BPF between the electric vehicle battery and the grid. They act as the interface between the high-voltage DC battery system of the EV and the grid allowing for efficient conversion of DC power to AC power during V2G energy injection and vice versa during G2V charging. The Taxonomy of RDCs is given in Figure 5.

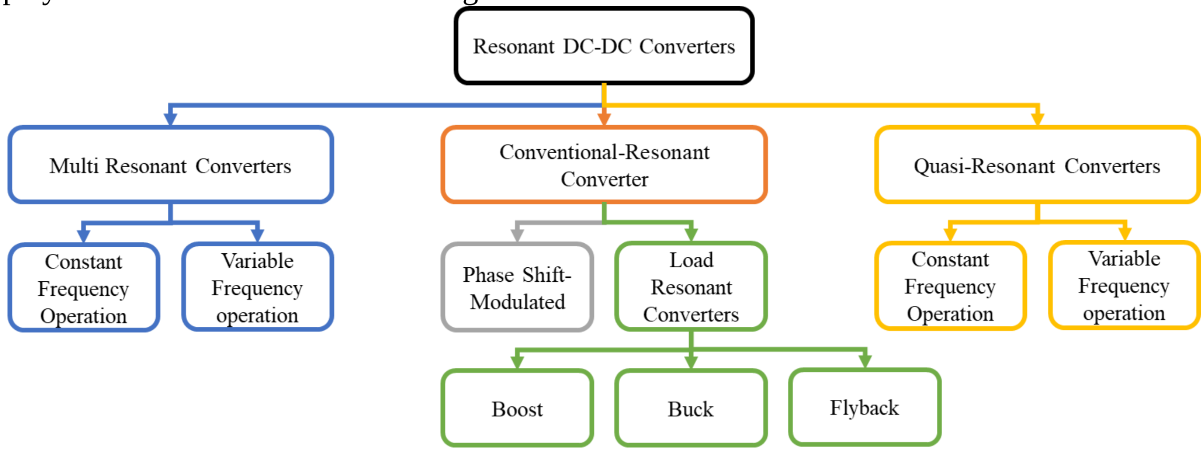

Figure 5. Taxonomy of Resonant DC-DC Converters

One of the key advantages of RDCs in V2G systems is their ability to achieve soft-switching operations. Soft-switching refers to the reduction of switching losses and electromagnetic interference, resulting in improved converter efficiency and reduced stress on the power semiconductor devices. This is accomplished by utilizing resonant components to create a controlled voltage or current waveform that enables smooth transitions during switching operations. Furthermore, RDCs offer enhanced power quality by reducing harmonics and improving the overall waveform of the AC power delivered to the grid. This is particularly important in V2G systems as maintaining grid compatibility and minimizing disturbances is crucial for the stability and reliability of the electrical grid.

RDCs are available in various topologies such as the Series RC, Parallel RC and Inductor-Inductor (LLC) RC and each topology has its advantages and considerations depending on factors such as power level, voltage range and efficiency requirements of the V2G system. In [21], their main aim was to provide a survey on the LLC RC so authors reviewed different RC topologies utilized for charging the EVs and then classified them. The authors have provided a guide for the development of the best converter for charging EVs. In this review, based on the reactive elements inside the RC topology, 3-element, 2-element and multi-element RC have been classified. In this work, different modulation and control methods for the LLC RC have been discussed for providing BPF in the V2G-EVs. In [22], authors have proposed a BRC which can reconfigure itself for different ranges of voltage gains using the soft-switching method. The reconfiguring process is done using an auxiliary switch which will switch among the CLLC-C or CLLC. Furthermore, the presented RC method addresses the problems of soft-switching in the V2G and G2V. The results are attained using the simulation and compared with the existing works. In [23], an optimization method has been presented for minimizing the cost of the LLC and for enhancing the controlling frequencies during the discharging (V2G) and charging (G2V) of the EVs. This work has not considered any kind of bi-directional charger. The results show that the proposed method reduces the cost and provides better-controlling frequencies for charging the EVs.

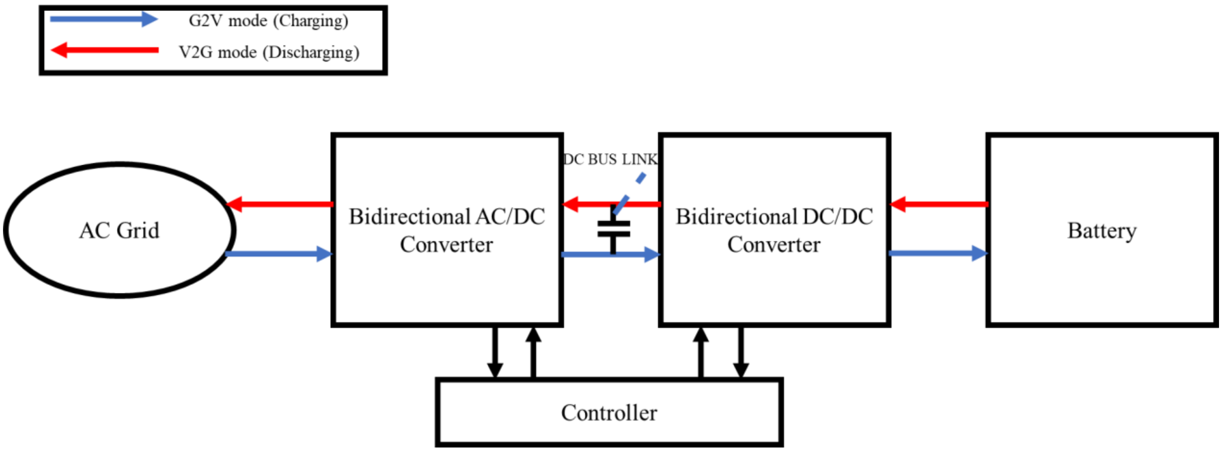

Figure 6. EV bidirectional charger topology [23].

In [24], an isolated Bi-directional-Resonant DC-DC Converter (BRDC) for charging the EVs is presented. This work uses the CLLL structure for the resonant circuit. By using the CLLL structure, the model can reduce the cost, provide better efficiency and reduce power loss. The converter has been designed on the Wide-Band-Gap Transistor switches for providing better power efficiency and density. Furthermore, this converter has used the Genetic-Algorithm and Particle-Swarm Optimization Algorithms for optimizing the PID controller. The results have been compared with the Si-based switching methods. The results show that the BRDC has attained 96.67% and 97.40% power efficiency for the discharging and charging respectively in the EVs. In [25], authors have given the cost of charging the EVs using various methods and topologies.

Overall, the utilization of resonant DC-DC converters in V2G electric vehicle systems offers significant benefits including high efficiency, reduced switching losses, improved power quality and compact size. These converters contribute to the optimization of power flow control, energy management and grid stability in V2G applications. Continued research and development in this area aim to further enhance the performance and reliability of resonant DC-DC converters supporting the integration of electric vehicles into the grid and promoting sustainable transportation solutions.

2.3 Multi-level Inverters (MLIs)

Multi-level inverters are a type of power electronic converter used in V2G-EV systems to efficiently convert DC power from the vehicle battery to AC power that can be injected into the grid. These inverters are designed to overcome the limitations of traditional two-level inverters by utilizing multiple voltage levels resulting in improved waveform quality, reduced harmonic distortion and increased power handling capabilities. In a V2G system, the multi-level inverter acts as the interface between the high-voltage DC battery system of the electric vehicle and the grid, enabling BPF. The primary objective of the multi-level inverter is to convert the DC power from the vehicle battery to AC power at the desired grid frequency and voltage level. Unlike conventional two-level inverters, which have only two voltage levels (positive and negative), multi-level inverters utilize multiple voltage levels to synthesize a staircase waveform that closely approximates a sine wave. This staircase waveform is achieved by using a series of power semiconductor switches and capacitors or DC sources which allow the output voltage to be stepped up or down in a controlled manner. The advantages of multi-level inverters in V2G systems are numerous. First and foremost they offer improved power quality by reducing the levels of harmonic distortion in the output waveform. This is particularly important in V2G applications as it helps to minimize the impact of injected power on the grid and ensures compliance with grid regulations and standards. The taxonomy of the multi-level inverters is given in Figure 7.

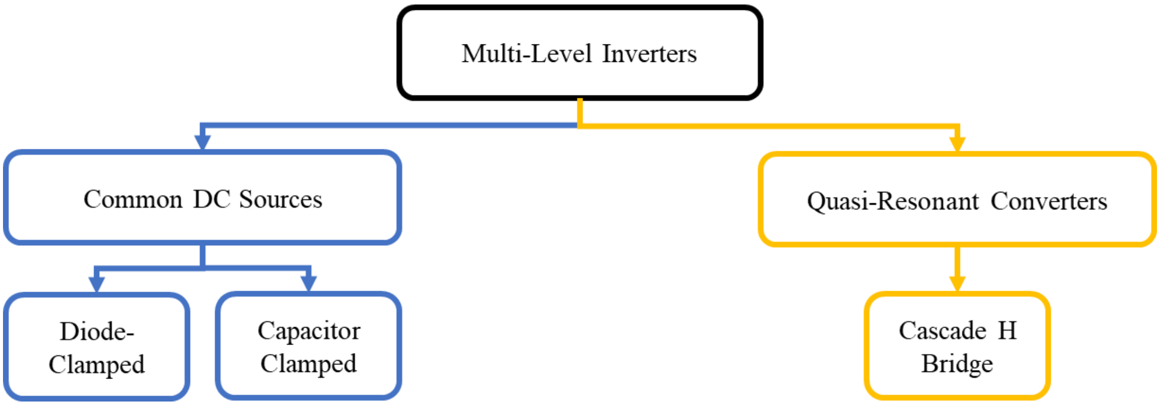

Figure 7. Taxonomy of Multi-Level Inverters.

Furthermore, multi-level inverters enable higher voltage levels to be achieved with lower voltage stress on the power semiconductor devices. This results in reduced switching losses improved overall efficiency and increased power handling capabilities. The ability to operate at higher voltage levels also allows for longer transmission distances making MLIs suitable for V2G systems that require power injection into the grid over extended distances. MLIs are available in various configurations including the diode-clamped (neutral-point clamped) inverter, flying capacitor inverter and cascaded H-bridge inverter. Each configuration offers different trade-offs in terms of cost, complexity and voltage levels.

In [26], authors have presented the different topologies for the MLI to provide the DC in the V2G environment for the EVs. The MLI can convert the DC to AC having a better output-voltage waveform. This study's main aim was to study how MLI can be used for providing better integration of the DC in the V2G applications. In [27], authors have investigated the advantages of using an MLI bi-directional charger for charging the EVs in the V2G and proposed a model to provide better power efficiency during discharging and charging. The simulation of this work has been done in MATLAB. The results show that the proposed model provides better results in comparison to the existing work. In [28], authors have proposed a model by considering the MLIs for the fast charging of EVs. This model comprises of two-layer Finite-Control Set-Model Predictive-Control Layer and Integrated-Perturbation Analysis and Sequential-Quadratic-Programming Layer. Both these layers are responsible for regulating the current and voltages as well as handling the non-linearities during the fast charging. In [29] and [28] authors have used the same MLIs for the fast charging of EVs. Their main aim was to provide DC having energy-efficiency. The model was designed using the Fuzzy and PID controller and the simulation was done on MATLAB. For achieving better system efficiency the Fuzzy controller has been used in this work. The results show that the proposed model attains better performance in terms of Total Harmonic-Distortion.

Despite the advantages multi-level inverters also present challenges such as increased complexity and higher component count compared to conventional two-level inverters. Additionally, the control of multi-level inverters can be more intricate due to the larger number of voltage levels and switches involved. However, advancements in control strategies and power semiconductor technologies have addressed many of these challenges making multi-level inverters a viable option for V2G electric vehicle systems. In conclusion, multi-level inverters are a promising solution for V2G electric vehicle systems as they offer improved power quality, reduced harmonic distortion and increased power handling capabilities. These inverters enable efficient BPF between the vehicle battery and the grid supporting the integration of electric vehicles into the power grid and promoting sustainable energy management. Ongoing research and development in multi-level inverter technology aim to further enhance their performance, efficiency and reliability in V2G applications.

2.4 Structural Hybrid of Reviewed Converters

In the reviewed converters for V2G electric vehicle systems mentioned above, there is a possibility of exploring a structural hybrid approach that combines the advantages of different converter topologies to achieve enhanced performance and efficiency. By integrating multiple converter topologies the structural hybrid approach aims to address the limitations and optimize the overall system performance in V2G applications. For example, a structural hybrid approach could involve combining the bidirectional DC-DC converter with a resonant converter or a multi-level inverter. This hybridization can offer several benefits. Firstly, incorporating a bidirectional DC-DC converter allows for efficient BPF between the vehicle battery and the grid. It enables energy transfer in both directions, enabling the vehicle to charge from the grid and inject surplus energy back into the grid during V2G operation. Adding a resonant converter to the hybrid structure can enhance the efficiency and power quality of the overall system. The resonant converter's soft-switching characteristics can reduce switching losses and improve overall converter efficiency. Additionally, it can mitigate harmonic distortion and reduce the impact on the grid ensuring compliance with power quality standards.

Furthermore integrating a multi-level inverter into the hybrid structure can provide improved waveform quality and increased power handling capabilities [30]. The multi-level inverter's ability to synthesize a staircase waveform with reduced harmonic content can enhance the power quality of the AC output making it suitable for grid injection [31]. Moreover, the increased voltage levels offered by the multi-level inverter can support longer transmission distances and reduce losses during power transfer [32]. By combining the bidirectional DC-DC converter, resonant converter, and multi-level inverter, the structural hybrid approach can take advantage of the strengths of each topology. This integration can result in a converter system that exhibits enhanced efficiency, improved power quality and increased power handling capabilities, ultimately optimizing the performance of V2G electric vehicle systems [33]. However, it is important to note that implementing a structural hybrid approach requires careful design and control considerations. In conclusion, a structural hybrid approach that combines the bidirectional DC-DC converter with a resonant converter and multi-level inverter can offer significant advantages in V2G electric vehicle systems. This approach has the potential to enhance efficiency, power quality and power handling capabilities contributing to the optimal integration of electric vehicles into the power grid.

2.4.1 Bidirectional Resonant Converters

Bidirectional resonant converters have gained significant attention in V2G (Vehicle-to-Grid) electric vehicle systems as a promising solution for efficient power conversion between the vehicle battery and the grid. These converters leverage have advantages of both BPF and resonant circuitry to enable high-efficiency energy transfer [34]. In a V2G system, bidirectional resonant converters serve as the interface between the high-voltage DC battery system of the electric vehicle and the AC power grid. The key principle behind bidirectional resonant converters lies in the use of resonant components, such as inductors and capacitors which is used to achieve soft-switching operation. Soft-switching minimizes switching losses and reduces stress on the power semiconductor devices and enhances overall converter efficiency. The resonant circuitry enables the converter to operate at high frequencies, which leads to compact size, reduced component stresses and improved power quality [35]. The bidirectional operation of resonant converters is achieved through the control of switches and resonant components. During charging the converter transfers energy from the grid to the vehicle battery, utilizing the resonant circuitry to maintain high efficiency and high-frequency operation. During vehicle-to-grid energy supply, the converter facilitates the transfer of energy from the vehicle battery back to the grid again utilizing the resonant circuitry to optimize power conversion [36].

One advantage of bidirectional resonant converters in V2G systems is their ability to achieve high power density and high efficiency. The resonant circuitry enables soft-switching which reduces losses and improves the overall converter efficiency. This in turn allows for efficient bidirectional power transfer between the vehicle and the grid minimizing energy losses and maximizing the utilization of renewable energy sources [37]. Another advantage is the improved power quality offered by bidirectional resonant converters. By leveraging resonant circuitry, these converters can reduce harmonics and improve the waveform quality of the AC power injected into the grid. This is particularly important in V2G systems as it helps to maintain grid stability, reduce grid disturbances and comply with power quality standards [38]. Furthermore, bidirectional resonant converters can provide galvanic isolation between the vehicle battery and the grid. This isolation can enhance the safety and protection of the vehicle and the grid preventing potential electrical hazards and ensuring reliable power transfer [39]. However, it is important to note that the design and control of bidirectional resonant converters require careful consideration. In conclusion, bidirectional resonant converters offer significant potential for efficient power conversion in V2G electric vehicle systems. They leverage resonant circuitry to achieve soft-switching operation, high efficiency, improved power quality and galvanic isolation.

2.4.2 Multi-level Bidirectional DC-DC Converters

Multi-level bidirectional DC-DC converters have emerged as a promising solution for efficient power conversion in V2G (Vehicle-to-Grid) electric vehicle systems. These converters combine the advantages of multi-level converter topologies and BPF to enable high-efficiency energy transfer between the vehicle battery and the grid [40]. In V2G systems bidirectional DC-DC converters play a crucial role in facilitating power exchange between the high-voltage DC battery system of the electric vehicle and the AC power grid. They allow energy to flow bidirectionally enabling the vehicle to draw power from the grid during charging and inject surplus energy back into the grid during vehicle-to-grid energy supply [41].

The concept of multi-level bidirectional DC-DC converters involves the use of multiple voltage levels to achieve efficient power conversion. Instead of relying on a single voltage level, these converters utilize several voltage levels which allow the reduction of voltage stress on the power semiconductor devices and improved power quality. The multiple voltage levels are created by using a combination of power semiconductor switches and energy storage elements such as capacitors or inductors [42].

One of the key advantages of multi-level bidirectional DC-DC converters in V2G systems is their ability to achieve high power density and high efficiency. By utilizing multiple voltage levels these converters can handle higher power levels while reducing losses and improving overall efficiency. This is particularly important in V2G applications where efficient power transfer is essential to maximize the utilization of renewable energy sources and minimize energy losses [43]. Furthermore, multi-level bidirectional DC-DC converters offer enhanced power quality. The use of multiple voltage levels enables the synthesis of a staircase waveform with reduced harmonic content resulting in improved waveform quality of the AC power injected into the grid. This helps to maintain grid stability, minimize grid disturbances and comply with power quality standards [44]. Moreover, multi-level bidirectional DC-DC converters can provide galvanic isolation between the vehicle battery and the grid. It is worth noting that the design and control of multi-level bidirectional DC-DC converters require careful consideration. Factors such as converter topology selection, voltage level determination, control strategies and system integration should be optimized to achieve the desired performance, efficiency and power quality. In conclusion, multi-level bidirectional DC-DC converters offer significant potential for efficient power conversion in V2G electric vehicle systems. By combining the advantages of multi-level converter topologies and BPF these converters enable high power density, high efficiency, improved power quality and galvanic isolation.

2.4.3 Multi-level Resonant Converters

Multi-level resonant converters have gained attention as a viable solution for efficient power conversion in V2G-EV systems. These converters combine the advantages of multi-level converter topologies and resonant circuitry to enable high-efficiency BPF between the vehicle battery and the AC power grid [45]. In V2G systems multi-level resonant converters act as the interface between the high-voltage DC battery system of the electric vehicle and the grid. They facilitate the bidirectional exchange of power allowing the vehicle to draw energy from the grid during charging and inject surplus energy back into the grid during vehicle-to-grid energy supply [46]. The key principle behind multi-level resonant converters lies in the utilization of resonant circuitry to achieve soft-switching operation [47]. Soft-switching minimizes switching losses, reduces stress on the power semiconductor devices and enhances overall converter efficiency. The resonant circuitry enables the converter to operate at high frequencies, leading to compact size, reduced component stresses and improved power quality.

One of the main advantages of multi-level resonant converters in V2G systems is their ability to achieve high efficiency and improved power quality. The resonant circuitry allows for reduced switching losses and enhanced power conversion efficiency. Additionally, it helps to reduce harmonics and improve the waveform quality of the AC power injected into the grid. This is crucial in V2G applications to ensure compliance with power quality standards and minimize the impact on the grid [48]. Furthermore, multi-level resonant converters offer the capability to handle high power levels and accommodate BPF. By utilizing multiple voltage levels these converters can support higher power ratings and voltage levels making them suitable for V2G systems with varying energy demands. The bidirectional operation allows for energy transfer from the grid to the vehicle battery during charging and vice versa during vehicle-to-grid energy supply. In conclusion, multi-level resonant converters offer significant potential for efficient power conversion in V2G electric vehicle systems. By combining the advantages of multi-level converter topologies and resonant circuitry these converters enable high efficiency, improved power quality and BPF.

2.4.4 Multi-level Bidirectional Resonant Converters

Multi-level bidirectional resonant converters have emerged as a promising solution for efficient power conversion in V2G (Vehicle-to-Grid) electric vehicle systems. These converters combine the advantages of multi-level converter topologies, BPF and resonant circuitry to enable high-efficiency energy transfer between the vehicle battery and the AC power grid [49]. In V2G systems multi-level bidirectional resonant converters serve as the interface between the high-voltage DC battery system of the electric vehicle and the grid. They facilitate BPF, allowing the vehicle to draw energy from the grid during charging and inject surplus energy back into the grid during vehicle-to-grid energy supply [50]. The concept of multi-level bidirectional resonant converters involves the integration of multiple voltage levels and resonant circuitry to achieve efficient power conversion. By utilizing multiple voltage levels these converters can handle higher power levels while reducing losses and improving overall efficiency. The resonant circuitry enables soft-switching operation which minimizes switching losses, reduces stress on the power semiconductor devices and enhances overall converter efficiency [51].

One of the key advantages of multi-level bidirectional resonant converters in V2G systems is their ability to achieve high power density and high efficiency. The combination of multi-level topology and resonant circuitry allows for efficient power transfer at high frequencies, resulting in compact size, reduced component stresses and improved power quality. This is particularly important in V2G applications where efficient power transfer is essential to maximize the utilization of renewable energy sources and minimize energy losses. Furthermore, multi-level bidirectional resonant converters offer enhanced power quality. The resonant circuitry enables soft-switching, which reduces switching losses and minimizes harmonic distortion. This results in improved waveform quality of the AC power injected into the grid, ensuring compliance with power quality standards and minimizing the impact on the grid [52]. Moreover, multi-level bidirectional resonant converters provide galvanic isolation between the vehicle battery and the grid. Isolation is important for safety and protection, preventing potential electrical hazards and ensuring reliable power transfer between the vehicle and the grid [53]. In conclusion, multi-level bidirectional resonant converters offer significant potential for efficient power conversion in V2G electric vehicle systems. By combining the advantages of multi-level converter topologies, BPF, and resonant circuitry, these converters enable high power density, high efficiency, improved power quality and galvanic isolation.

3 Issues and Challenges

Bidirectional DC-DC Converters, Resonant Converters, Multilevel Inverters, Bidirectional Resonant Converters, Multi-level Bidirectional DC-DC Converters, Multi-level Resonant Converters and

Multi-level Bidirectional Resonant Converters offer significant potential for power conversion in V2G (Vehicle-to-Grid) electric vehicle systems. However, authors also face certain issues and challenges that need to be addressed for their successful implementation. Some of these challenges include:

1. Efficiency: One of the primary concerns is achieving high conversion efficiency in bidirectional power converters. Both DC-DC converters and resonant converters must minimize switching losses and optimize power transfer efficiency in both directions. Improving efficiency is crucial to maximize energy utilization and minimize losses during energy exchange between the vehicle and the grid.
2. Power Density and Size: Electric vehicles often have limited space for power electronics. Therefore compact and high-power-density converters are essential for integration into the vehicle. The challenge lies in designing and optimizing the converters to achieve high power density without compromising efficiency and performance.
3. Thermal Management: Efficient thermal management is critical for the reliable operation and longevity of power converters. The high-power levels and BPF can lead to increased heat generation which requires effective cooling techniques to prevent thermal stress and maintain converter performance.
4. Voltage and Current Stress: Bidirectional power converters experience voltage and current stress in both directions which can affect the performance and lifespan of the converter components including power semiconductors, capacitors and inductors. Managing voltage and current stress is vital to ensure the durability and reliability of the converter.
5. Control and Synchronization: Accurate control and synchronization are crucial for bidirectional power converters to operate seamlessly within the V2G system. The control algorithms need to manage BPF maintain power quality and ensure stable grid integration. Synchronization with the grid frequency and voltage levels is also necessary for efficient power exchange.
6. Electromagnetic Interference (EMI): Power converters can generate electromagnetic interference that may affect the performance of other electronic systems in the vehicle or the grid. EMI mitigation techniques and proper shielding are required to minimize the impact of EMI and comply with electromagnetic compatibility standards.
7. Cost and Scalability: The cost-effectiveness and scalability of power converters are important factors for widespread adoption in V2G systems. Reducing the cost of components, optimizing manufacturing processes and ensuring scalability to different power levels and vehicle models are challenges that need to be addressed.
8. Grid Compatibility and Standards: V2G systems must comply with grid regulations and standards to ensure safe and reliable integration. Bidirectional power converters should meet the necessary grid codes, voltage and frequency requirements and communication protocols to enable seamless interaction with the grid infrastructure.

Addressing these challenges through continued research advanced design techniques and optimization strategies will contribute to the successful implementation of bidirectional DC-DC converters, resonant converters, multilevel inverters and their combinations in V2G electric vehicle systems. Overcoming these challenges will pave the way for efficient and sustainable integration of electric vehicles into the power grid facilitating a greener and more reliable energy ecosystem.

4 Conclusion

The exploration of bidirectional power converters in V2G (Vehicle-to-Grid) electric vehicle systems offers significant potential for efficient power conversion and the integration of electric vehicles into the power grid. Throughout this survey, we have examined various types of converters including bidirectional DC-DC converters, resonant converters, multilevel inverters, bidirectional resonant converters, multi-level bidirectional DC-DC converters, multi-level resonant converters and multi-level bidirectional resonant converters. These converters have shown promise in addressing the challenges associated with V2G systems such as varying energy demands, intermittent charging patterns and the need for efficient power transfer. They enable BPF to allow electric vehicles to draw energy from the grid during charging and inject surplus energy back into the grid during vehicle-to-grid energy supply. We have discussed the advantages of these converters, including high efficiency, improved power quality, power density and galvanic isolation. They offer opportunities for reducing losses, improving waveform quality, handling high power levels, and ensuring safety and protection during power exchange. However, some challenges need to be addressed. These challenges include optimizing efficiency, managing power density and size constraints, addressing thermal management, handling voltage and current stress, implementing accurate control and synchronization, mitigating electromagnetic interference, ensuring cost-effectiveness and scalability, and complying with grid compatibility and standards. Addressing these challenges will require ongoing research, advanced design techniques, and optimization strategies. By overcoming these obstacles, we can achieve efficient power conversion, reliable grid integration, and the advancement of sustainable energy systems.

In conclusion, the exploration and development of bidirectional power converters in V2G electric vehicle systems hold great promise for facilitating the transition to sustainable transportation and optimizing the utilization of renewable energy sources. To realize the full potential of V2G systems, it is necessary to develop advanced bi-directional power converters that not only efficiently transfer power between the vehicle and the grid but also address the unique requirements of electric vehicle charging and grid integration. These converters should offer high efficiency, compact size, improved power quality and seamless BPF management.

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Abbreviations

Abbreviation	**Full Form**
EV	Electric Vehicle
V2G	Vehicle-to-Grid
BDPF	Bi-Directional Power-Flow
BPC	Bi-directional Power Converters
BDC	Bi-directional DC-DC Converters
RC	Resonant-Converters
MLI	Multi-Level Inverters
BRC	Bi-directional-Resonant Converters
MLBDC	Multi-Level Bi-directional DC-DC converters
MLC	Multi-Level-Converters
MLBRC	Multi-Level Bi-directional Resonant-Converters
BEVs	Battery EVs
PEVs	Plug-in Hybrid EVs
ICE	Internal-Combustion Engine
PECs	Power-Electronic Converters
AC-DC	Alternative Current to Direct Current
DC-AC	Direct Current to Alternative Current
DC-DC	Direct Current to Direct Current
AC-AC	Alternative Current to Alternative Current
UPS	Uninterruptible Power-Supplies
PWM	Pulse-Width-Modulation
BPF	Bi-directional Power-Flow
PID	Proportional-Integral Derivative
V2G-EV	Vehicle to Grid Electric Vehicle
G2V	Grid-to-Vehicle
RDC	Resonant DC-DC Converter
LLC	Inductor-Inductor
CLLC	Capacitor-Inductor-Inductor-Capacitor
CLLC-C	Capacitor-Inductor-Inductor-Capacitor-Capacitor
BRDC	Bi-directional Resonant DC-DC Converter