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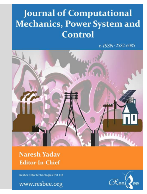

Analysis of Compensation Topologies for Enhanced Bidirectional WPT Control in Electric Vehicle Systems

K. Rajkumar

Department of Mechanical Engineering,
J. P. College of Engineering, Tenkasi, Tamilnadu, India-627852
krajkumark@gmail.com
rajkumarksafety@gmail.com

Abstract: Vehicles with internal combustion engines (ICEs) are being replaced by electric vehicles (EVs) as a result of the constantly growing demand for energy. Utilizing EVs also has the benefit of increasing the penetration of renewable energy sources because the batteries can be used as an energy storage device. Vehicle-to-Grid (V2G) technology has enabled significant advances in EVs, including grid integration. Power transfer between the grid and the EV batteries is made possible using a bidirectional technology. Bidirectional Wireless Power Transfer (BWPT) is another technique that can help users automate the power transfer process to reduce the need for human interaction. On the other hand, a suitable vehicle and grid synchronization with adequate control and compensation networks are necessary for an efficient BWPT. The literature has presented some compensating strategies to increase the WPT model's efficacy and reliability. Performance measures, implementation tools, performance obtained through numerous methods, and types of coupling are used to analyze the examined works.

Keywords: Bidirectional-Wireless power transfer technique, Controller, DC-DC converter; Electric Vehicle, Optimization.

Nomenclature

Abbreviations	Descriptions
ICE	Internal Combustion Engine
EVs	Electric Vehicles
V2G	Vehicle-to-Grid
BWPT	Bidirectional Wireless Power Transfer
WPT	wireless power transfer
ZVS	Zero-Voltage Switching
PWM	Pulse Width Modulation
G2V	grid-to-vehicle
SS	Series-series
SP	Series parallel
PP	Parallel Parallel
PS	Parallel Series
IPT	Inductive Power Transfer
BIWPTS	Bidirectional Inductive Wireless Power Transfer System
3D-FEM	Three-Dimensional Finite Element
MEPT	Maximum Efficiency Point Tracking
GSSA	Generalized State Space Averaging
EDF	Extended Describing Function
ESSs	Energy Storage Systems
UPS	Uninterrupted Power Supply
SAHFWPT	Single Active High-Frequency WPT
DAHFWPT	Dual Active High-Frequency WPT
EPS	Extended Phase Shift
TPS	Triple-Phase-Shift
WCS	Wireless Charging System
LCL	Inductor–Capacitor–Inductor

1. Introduction

When it comes to lowering greenhouse gas emissions, EVs are thought to be a desirable substitute for traditional vehicles that are mostly built on ICEs. Recent developments in battery technology, power electronics interfaces, electric motors, and energy management control have led to a notable increase in the industrialization of electric vehicles in the past few years. While EV usage is rapidly increasing, significant hurdles remain before widespread adoption, including high battery costs, limited range, slow charging speeds, insufficient charging infrastructure, low energy density, weight, and reliability concerns. The absence of suitable infrastructure, such as charging stations, serves as one of the primary obstacles to the growth of EVs.

Electric vehicles can now be charged without a physical connection due to recent advancements in WPT technology. In the meantime, WPT technology is utilized in commercially accessible fast-charging systems, such as city battery buses. This alternate charging method has shown to be highly dependable in its application. The main drawback of WPT technology is its reduced receiver power and transfer efficacy as contrasted with electrical charging methods. At a constant air gap, the coupling factor is typically proportionate to the size of the loosely connected transformer. The majority of recent work in WPT research has concentrated on resonant circuit topologies and control strategies for inverters and converters, whether they are used on the load side or the charger side. Two common resonant circuit architectures, the series and parallel connected circuits, have been evaluated in earlier studies for various purposes. These configurations serve as the primary and secondary resonant circuits [1-3].

The contribution of the paper is,

- To analyze and review recent research papers on various compensation techniques of Bidirectional wireless power transmission in EV.
- To evaluate the performance of the works in terms of power, frequency, and efficiency.

This paper is structured as follows: Section 1 provides an overview of bi-directional WPT in EVs. State-of-the-art methods are examined in Section 2, followed by an analysis and discussion in Section 3. Research gaps are identified in Section 4, with concluding remarks presented in Section 5.

2. Research based on State of the art

A bidirectional AC-DC converter, a DC-AC converter, compensators, and coupling coils form the fundamental building blocks of the BWPT system. A full-bridge converter topology, consisting of four switches (Q1-Q4), regulates forward power transmission. During reverse current flow, the diode permits positive current passage. In this mode, the inverter operates with a DC source as input and delivers power to a load comprising coupled coils, compensation circuits, a converter, and a battery. AC power generated by the load is rectified to supply the inverter. A compensation circuit is essential for the resonant operation and is positioned between the inverter and the primary coil. The primary coil, energized by AC, produces a magnetic field whose intensity is determined by current magnitude and frequency. In the literature, different types of compensation, such as SS, SP, PP, PS, and others, are also considered.

The same converter topology is employed on both the transmitter and receiver sides, enabling bidirectional operation (G2V/V2G). In these modes, circuit components experience varying conditions as the battery transitions between charging and discharging states. The secondary-side converter functions as both a charger and inverter, while the primary-side converter operates as a rectifier instead of an inverter. The function of a power converter, operating as either a rectifier or inverter, depends on the power flow direction. In BWPT systems, a full-bridge converter primarily defines the resonant circuit, while generating harmonics to reduce primary and secondary coil losses. Phase-shift and phase-angle control methods are commonly used to regulate power transfer. PWM is employed to enhance system efficiency over extended transmission distances.

2.1 Conventional Models

In 2016, A. A. S. Mohamed, *et al.* [8] developed a harmonics-based theoretical power-flow model for BIWPTS for charging and discharging EVs in V2G applications. Accurately estimating active and reactive power flow in both V2G and G2V modes, the model further investigates the influence of circuit losses and harmonics generated by high-frequency inverters on overall power flow performance. The impact is mathematically described by four power flow criteria formulas. To validate their effectiveness, a computer model and an experimental platform simulating the BIWPTS for EV applications were designed and tested.

In 2015, Jun-Young Leeand Byung-Moon Han [12] implemented an alternative approach for a large air-gap bidirectional WPT EV charger. Leveraging self-inductance and a resonant capacitor to determine the operating frequency, this system employs self-resonant PWM (SR-PWM) for control, achieving constant frequency operation independent of air gap variations (12-20 cm) and eliminating the need for an additional current chopper. This approach has been successfully validated with a 6.6-kW prototype.

In 2014, Akshaya K. Swain, *et al.* [17] adopted a multivariable dynamic model for a multi-pickup bidirectional IPT system, which can provide an accurate insight into the behavior of this system and can be used for controller synthesis under variations of component values. Frequency domain analysis is employed to assess the system's output sensitivity to various parameters, explore the interaction between control variables, and evaluate the overall controllability. Experimental measurements convincingly validate the model's ability to accurately predict the dynamic behavior of bidirectional IPT systems with multiple pickups. This makes it a valuable tool for both dynamic analysis and controller design.

In 2017, Yunyu Tang, *et al.* [23] planned a new controller that uses measured active power (P) and reactive power (Q) at the resonant network of BD-WPT systems to regulate the power flow in both directions while providing synchronization between two sides without a dedicated communication interface for controlling power transfer. Experimental results validate that the suggested controller manages power flow within BD-WPT systems.

In 2018, Kerui Li and Siew-Chong Tan [26] established the use of a class E2 inverter-rectifier system with phase-shift control for bidirectional wireless power transfer applications. By adjusting the phase shift ratio between the inverter and rectifier driving signals, the controller regulates power flow within the system. Simulation results confirm its applicability and robustness.

2.2 Compensation Strategies

Within the compensating concepts, the fundamental principle of Ohm's law is applied. According to Ohm's law, whenever current passes via a resistor, there is a little voltage drop over it. This voltage drop will be in opposition to the input power. Consequently, a second supply voltage is applied, whose polarity is the opposite of that of the source voltage and whose magnitude correlates to the voltage drop. The compensatory hypotheses function based on this concept. Compensation arrangements are another crucial element in enhancing resilience to coupling factor variation. Various techniques of compensation are applied to raise the voltage in the system.

2.2.1 Series – Series Compensation

Series-series compensation is an approach utilized to increase system reliability and efficacy in WPT systems. Enhancing power transfer capabilities, lowering losses, and improving the WPT process' overall efficiency are the main objectives. Series-series compensation requires connecting reactive components in series with the transmitter and receiver coils.

A design optimization strategy was provided for an SS WPT system in 2018 by Yang Yang *et al.* [2]. An SS-compensated WPT system was developed for 3.7 kW and 7.7 kW charging, operating at 40 kHz and 85 kHz resonance frequencies. Optimized coil dimensions and system efficiency were achieved. Unidirectional rectifiers/inverters and DC-DC converters were integrated to enable G2V operation. Modeling and magnetic testing results indicate that this WPT system holds significant promise for light-duty EV applications.

Marojahan Tampubolon, *et al.* [3] concentrated on a bidirectional resonant WPT system with high efficacy in 2023. After presenting the series-series compensated WPT analysis, the established bidirectional WPT system's concept is examined. Finally, to demonstrate the viability as well as the reliability of the suggested design, the operation and testing findings for a 3-kW laboratory prototype are also demonstrated.

The research conducted in 2020 by Emilio J. Molina-Martínez et al. [4] concentrated on the control system layout utilized for a bidirectional IPT charger that can function in both G2V and V2G modes. Despite using an SS compensation topology, the IPT system's control layout strategy can be expanded to accommodate the incorporation of different compensating schemes. This is made possible by the application of the well-known root-locus method. Additionally, as this value rises, the control system can be employed to control the primary side's current peak value, safeguarding the IPT system.

In 2014, Nguyen Xuan Bac, *et al.* [7] suggested an optimal phase shift modulation technique to decrease the coil losses of a SS compensated BIPT system. Furthermore, an extensive analysis of power converters that affect the system's overall efficacy is also provided. To maximize the BIPT system's overall efficacy, a closed-loop controller is suggested. The suggested system offers high effectiveness throughout a broad range of output power, and the outcomes strongly show its applicability.

A unique BWPT control technique was used in 2019 by Tian Tan *et al.* [10]. This approach can accomplish phase synchronization and MEPT without depending on the wireless connection in real-time. An SS-compensated BWPT system is analyzed without real-time wireless communication. A small-signal model, based on GSSA and EDF methods, is developed to address overshoot and oscillation issues inherent to the control strategy and system dynamics. The suggested control technique is utilized to develop and optimize a BWPT control system utilizing the small-signal model.

The development technique for an SS wireless system was devised by Tasnime Bouanou *et al.* [14] in 2023. This approach aids in determining the proper pad dimensions for delivering power to the electric vehicle battery. The optimal coupling effectiveness and performance are achieved by careful consideration of the development method. Additionally, this method is used to construct a magnetic design that is examined and modeled. The system can attain an efficacy level of up to 90.02% while avoiding the bifurcation phenomena, according to the simulated outcomes.

In 2023, Abhay Kumar *et al.* [15] developed two distinct strategies for controlling the power converters, and they predicted a thorough investigation of converter losses at various phases in conjunction with the SS-compensating coils in WPT systems. The SAHFWPT system and the DAHFWPT system are the two methods for wireless DC-DC power flow regulation. The dual-phase shift approach in DAHFWPT and the EPS in SAHFWPT regulate the converters' operations, correspondingly. Additionally, this section examines the workings and losses of the WPT system's unidirectional power flow, which runs from the primary side's DC bus to the secondary side's battery load. Loss estimation includes conduction, coil switching, and high-frequency switching losses. The converter's performance is critical to the WPT system's overall efficacy.

Long primary side-coupled systems benefit most from series compensation, which involves placing capacitors directly along the extended coil paths. However, series compensation necessitates higher voltage and current ratings compared to parallel compensation. SS compensation is more efficient for high-power applications with dynamic load characteristics, such as charging vehicles within multikilowatt loads. Series compensation is particularly advantageous for segmented dynamic WPT applications characterized by high secondary voltages and fluctuating coupling coefficients.

2.2.2 Parallel Compensation

Under IPT technology, U. K. Madawala and D.J. Thrimawithana [5] executed a new contactless, bi-directional power interface in 2013. To achieve bidirectional power flow and inherent short-circuit protection, the suggested architecture incorporates a parallel var compensator with regulated rectifiers on both system sides. A mathematical model has been developed to demonstrate how the system's direction and power flow are easily regulated by making adjustments to the converters' voltage in terms of magnitude or relative phase. Simulation and experimental results demonstrate that the suggested IPT system is workable and appealing for use in real-world settings.

2.2.3 LC Compensation

An inductive WPT system using a bidirectional current-fed half-bridge LC arrangement was created in 2017 by Suvendu Samanta *et al.* [20]. Evaluation and operation of current-fed resonant topologies with voltage doubling and current sharing are the main areas of interest. Therefore, the experimental findings are provided to support the evaluation and illustrate the effectiveness with which the system functions when there is bidirectional power flow.

A BD-IPT system of the series-tuned LC type was devised by Lei Zhao *et al.* [26] in 2015. To examine the system's behavior and susceptibility to circuit parameter variation, mathematical and simulation-based approaches have been created. The mathematical equations' accuracy is confirmed, and each system's effectiveness is examined through the use of simulated data derived from 3.7 kW simulated systems. For system efficacy optimization, both relative phase modulation and frequency modulation among converters are being explored.

2.2.4 LCL Compensation

A well-defined process for attaining the ideal LCL design with BIWPTS for EV applications was implemented by Ahmed A. S. Mohamed *et al.* [6] in 2017. Analytical models combined with electromagnetic field computations form the basis of the suggested approach. For an 8-kW polarized DD power pad, a 3D-FEM model was developed, optimized, and constructed. Additionally, MATLAB/Simulink was used to create the BIWPTS model.

A unique bidirectional IPT system was implemented in 2011 by Udaya K. Madawala *et al.* [9]. It is especially well-suited for applications where two-way power transfer is desirable, including plug-in electric vehicles and V2G systems. To provide controlled and bidirectional power transmission between EVs or equipment and the grid, each EV or piece of equipment uses a converter or reversible rectifier in conjunction with an LCL parallel resonant circuit. The suggested method is the best power interface, according to the outcomes, for the effective and contactless integration of several hybrid or electric vehicles.

The authors Chenyang XIA *et al.* [13] 2017 investigated a relay bidirectional WPT system utilizing LCL topologies to address inconsistencies in transfer distance, coil misalignment, and efficacy. The fundamental attribute, working modules, and variable layout and optimization of the suggested framework are all examined. Experimental studies validate these mathematical calculations, and this method's strong performance may allow it to be used in EV charging systems.

A dynamic model was developed in 2012 by Akshaya K. Swain *et al.* [18] and offers precise insight into the behavior of bidirectional IPT systems. To calculate the transfer function matrix of eight-order bidirectional IPT systems, a state space-based model is suggested, which is then constructed inside a multivariable framework and transferred into the frequency domain. To enable bidirectional power transmission between the track and the pick-up, nearly identical electronics, a tuned LCL circuit, and a reversible rectifier are used in the implementation of the primary and pick-up circuits.

2.2.5 Hybrid Compensation

A CLCS-LCL current-derived bi-directional WPT system with improved security and power transfer capacity was developed in 2018 by Yue Sun *et al.* [16]. It is a basic approach for looking at the distinct power features of the secondary and primary sides. Furthermore, a controlled rectifier bridge and a bi-directional DC/DC circuit are employed. The "constant primary current, constant secondary voltage" control approach can now be implemented as a result. At last, research findings confirm the viability and efficacy of the suggested approaches.

A hybrid WPT system that charges electric vehicles (EVs) at a consistent rate even in the face of significant charging pad misalignments was introduced by Lei Zhao *et al.* [22] in 2017. To ensure reliable and efficient charging, the proposed system integrates two distinct resonant networks (LCL and CL) in parallel but magnetically isolated configuration. This hybrid WPT system demonstrates high efficiency and maintains a consistent charging profile across a wide range of 3D pad misalignments.

2.2.6 LCC compensation

A bi-directional wireless power transmission system with double-sided LCC resonant tuning and an airgap spacing of 11 inches among the coils was established in 2020 by Omer C. Onar *et al.* [11]. The suggested system connects EV batteries with the AC grid, providing UPS functionality by dynamically distributing power between the stationary ESS, EV batteries, or both as needed. The system's operation and performance are demonstrated by its outcomes, which show total effectiveness ranging from 93% to 97%, based on the mode of operation.

Xiaoming Zhang, *et al.* [19] recommended a TPS control strategy to achieve load matching while realizing ZVS for all power switches within the entire power range. A time-domain model for the double-sided LCC compensation network was developed to analyze its ZVS operating range. Experimental validation confirmed the model's accuracy, with all switches achieving ZVS across the entire power spectrum and maximum efficacy.

A bidirectional DC-DC WPT using LCC-C resonance compensation was suggested by Hurng-LiahngJou, *et al.* [21] in 2020. Numerous benefits are demonstrated by the suggested bidirectional DC-DC WPT with LCC-C resonance adjustment. It has three functions: (1) bidirectional power flow; (2) constant current (CC) or constant voltage (CV) output; and (3) avoids burnout of the coil in the load side or misaligned coils. The findings from experiments confirm that a higher transmission efficacy is achieved with the developed bidirectional DC-DC WPT.

In 2021, Mostak Mohammad, *et al*. [24] presented the design and implementation of a bidirectional 20 kW WPT system with LCC-LCC compensation for medium-duty vehicle charging. Additionally, double-D (DD) coils were used in the design of the charging pads, switching components were used in the inverter and rectifier, and an LCC-LCC tuning circuit was used in the tuning networks. To confirm the suggested WCS's sensitivity, power transfer capability, and efficiency during load fluctuation, it was constructed, simulated, and tested. The largest airgap of the bidirectional WCS with the maximal power density as well as effectiveness is the one that is being suggested.

2.2.7 CLCL Compensation

A mathematical model for precisely characterizing the steady-state behaviour of BD-IPT systems was proposed by Duleepa J. Thrimawithana, *et al.* [27] in 2013. The steady-state behavior of CLCL-tuned BD-IPT systems is reliably predicted by the model, which was constructed by considering the harmonic effects and having the flexibility to integrate fluctuations in system variables and controller parameters. The importance and reliability of the suggested framework, which also has the potential to predict the system's losses, are shown by simulation findings during different operating situations.

3. Analysis and Discussion

This part provides an analysis and discussion regarding the study of performance as well as an evaluation of the findings, which highlights the significance of different bi-directional WPT system implementation methods for EVs. The Performance analysis of various bi-directional WPT is tabulated in Table 1, and Table 2 tabulates the compensation topologies.

Table 1. *Performance analysis of various bi-directional WPT*

Efficiency Analysis		Frequency range Analysis		Power analysis	
Efficiency	**Research papers**	**Frequency range**	**Research papers**	**Power**	**Research papers**
<80%	[8] [12]	20-40 kHz	[3] [4][7]	1-10 W	[14] [15]
80-85%	[17] [23] [26]	40-60 kHz	[20] [25]	51-100 W	[11] [19] [21]
85-90%	[9] [11] [13]	60-80 kHz	[27]	101-500 W	[21] [24]
90-95%	[3] [4] [5] [15] [18] [21] [24] [27]	80-100kHz	[6] [7] [9][11] [19]	501-1000 W	[2] [3] [4] [7][6] [7] [9]
95-100%	[1][2]	>100 kHz	[16] [22]	> 1 kW	[27][5]

Table 2. *Compensation network topology for bi-directional WPT system*

Type of Compensation	Research papers
Series compensation	[2] [3] [4] [7] [10] [14] [15]
Parallel compensation	[5]
LC compensation	[20] [25]
LCL compensation	[6] [7] [9] [13] [18]
LCC compensation	[11] [19] [21] [24]
CLCL Compensation	[27]
Hybrid compensation	[16] [22]

4. Research Gaps and Future Directions

a) Shortcomings

- The disadvantage of this system is the dependency of efficiency on the load [7].
- A design procedure for designing the optimal pad to transfer a specific power remains a big challenge for researchers [14].
- In multi-pickup systems, directly controlling the voltage of a single pickup (Vpi) to regulate its power delivery is not feasible due to its impact on the power delivered to other pickups.

b) Future Work

- Charging at public stations can be a hassle for EV owners because of parking limitations.
- Future efforts should focus on optimizing the system's efficiency, especially when handling small loads.
- A critical area for future investigation involves a comprehensive analysis of human safety concerns arising from magnetic field exposure during EV charging.

5. Conclusion

In this study, a comprehensive review of existing technological solutions for topologies of Compensation and the management of Wireless power Transfer technologies is given by reviewing recent papers. The concept of each solution is thoroughly reviewed and the feasibility is evaluated. Finally, a thorough comparison of technological solutions was made, considering the design and control requirements of the topology. According to our findings, more investigators have not adopted the secondary side control for WPT systems in EVs, which can thus be considered as the future research direction.

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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