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ENHANCED BIDIRECTIONAL WIREL ESS POWER TRANSFER FOR ELECTRIC VEHICLES USING PSO BASED SMC WITH PHASE SHIFT MODULATION

S. Gayathri[1], D. Hima Bindu[2], S.Sakunthala[3]

[1]P.G. Student, Department of Electrical and Electronics Engineering, SPMVV, Tirupati, India.

[2]Assistant Professor, Head of the Department, Department of Electrical and Electronics Engineering, SPMVV, Tirupati, India.

[3]Assistant Professor, Department of Electrical and Electronics Engineering, JNTUACEK – Kalikiri, India.

Abstract: This project presents an enhanced bidirectional wireless power transfer (BWPT) system for electric vehicle (EV) applications, utilizing Particle Swarm Optimization (PSO)-based Sliding Mode Control (SMC) with Phase Shift Modulation (PSM) for superior performance. The BWPT system enables seamless Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) operations, addressing key challenges such as power factor management, dynamic efficiency, and power transfer rates. While conventional dual-phase shift Pulse Width Modulation (PWM) techniques improve power factor correction (PFC) in unidirectional wireless power transfer (WPT) systems, bidirectional systems demand advanced control strategies to manage dual-side power converters effectively. The proposed PSO-SMC control framework optimizes the phase shift parameters, ensuring precise power flow regulation, enhanced stability, and reduced switching losses under varying load and grid conditions. Simulation results in MATLAB/Simulink demonstrate that the PSO-SMC with PSM significantly improves power factor, transfer efficiency, and overall system reliability, making it a robust solution for future EV charging infrastructure and smart grid integration.

Keywords: Bidirectional charging, electric vehicle, wireless power transfer, vehicle to grid, coil structure, bidirectional DC/DC converters, smart charging, SMC.

I. INTRODUCTION

The rapid adoption of Electric Vehicles (EVs) is reshaping the transportation sector by reducing reliance on fossil fuels and mitigating environmental concerns such as greenhouse gas emissions and urban air pollution. However, the growing EV population poses major challenges in charging infrastructure, where conventional plug-in charging systems face issues of mechanical wear, user inconvenience, and safety risks. To overcome these drawbacks, Wireless Power Transfer (WPT) has emerged as a promising solution, providing contactless, safe, and efficient charging [1-2].

Building on WPT, Bidirectional Wireless Power Transfer (BWPT) allows both Grid-to-Vehicle (G2V) charging and Vehicle-to-Grid (V2G) discharging. This functionality enables EVs to operate not only as loads but also as distributed energy resources, supporting renewable integration, load balancing, and smart grid operations. Such capabilities make BWPT essential for next-generation sustainable energy ecosystems.

Despite its potential, BWPT faces significant challenges in practical implementation. High Total Harmonic Distortion (THD) degrades power quality and stresses devices, while poor Power Factor Correction (PFC) reduces grid compliance. Coil misalignment during charging leads to reduced coupling efficiency and unstable operation, and efficiency losses due to switching and conduction further limit performance. These problems must be addressed to ensure reliable and large-scale deployment.

This paper contributes an enhanced BWPT system that integrates Particle Swarm Optimization–Sliding Mode Control (PSO-SMC) with Phase Shift Modulation (PSM). The PSO algorithm dynamically tunes controller parameters, while SMC provides robustness against nonlinearities and disturbances. PSM regulates bidirectional power transfer with minimal switching losses. Together, these techniques significantly reduce THD, improve PFC, enhance efficiency, and maintain stability under coil misalignment. The proposed solution is validated through MATLAB/Simulink simulations for both G2V and V2G modes, demonstrating improved power quality, efficiency, and grid compatibility.

II. Conventional Methodology

A. Conventional BWPT Systems

Conventional Bidirectional Wireless Power Transfer (BWPT) systems are designed to facilitate seamless energy exchange between electric vehicles (EVs) and the power grid in both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. These systems typically use high-frequency full-bridge converters on both sides, which are paired with resonant compensation networks—such as LCC or LCCL topologies—to ensure efficient energy transfer and minimize losses. Power flow is regulated using phase-shifted modulation techniques, where the relative timing between converter switches determines the direction and amount of energy transferred. On the EV side, rectifiers are employed to convert AC to regulated DC for battery charging. Such configurations enable bidirectional operation without mechanical connectors, offering convenience, safety, and improved grid interaction. Despite their advantages, challenges such as harmonic distortion, reduced power factor, and sensitivity to coil misalignment still need advanced control strategies for practical deployment in large-scale EV charging networks [3-6].

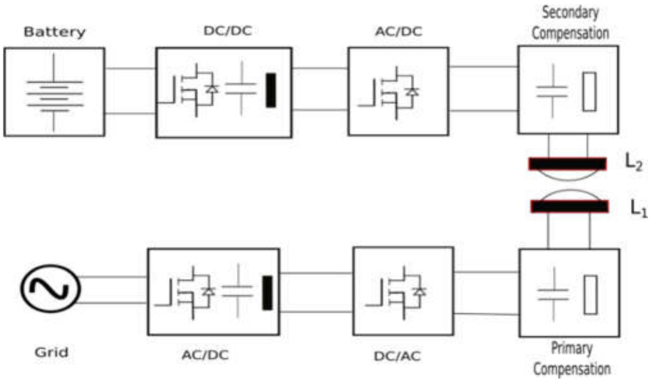

Fig 1: Block Diagram of Bidirectional Wireless Power Transfer System

B. Limitations of Existing Control Methods

Despite functional feasibility, traditional control approaches such as Phase Shift Modulation (PSM) and Proportional–Integral (PI) controllers suffer from several drawbacks. PSM is efficient but sensitive to coil misalignment, bifurcation phenomena, and variations in load or grid conditions. It also struggles to maintain low Total Harmonic Distortion (THD) and effective Power Factor Correction (PFC) under dynamic operation. On the other hand, PI-based controllers provide simple voltage and current regulation but lack robustness against nonlinearities and parameter variations, often leading to oscillations and reduced efficiency. These limitations hinder reliable large-scale deployment of BWPT for smart grid applications.

C. Research Gap

The literature reveals a gap in achieving simultaneous THD reduction, PFC improvement, and efficiency enhancement under uncertain and dynamic conditions such as coil misalignment and load variations. While existing PSM and PI-based schemes provide partial solutions, they do not offer adaptive and resilient control across both G2V and V2G modes. This motivates the development of a hybrid control framework that combines optimization and nonlinear robustness, enabling stable, efficient, and grid-compliant BWPT operation.

III. PROPOSED METHODOLOGY

A. Overview of BWPT Architecture

The proposed system adopts a high-efficiency Bidirectional Wireless Power Transfer (BWPT) architecture consisting of three main blocks:

Grid Side Converter (Primary Inverter): Converts DC from the grid into high-frequency AC for wireless transmission.

EV Side Converter (Secondary Inverter/Rectifier): Rectifies received AC to charge the battery in G2V mode or inverts stored DC to AC in V2G mode.

LCC–LCC Resonant Compensation Network and Coupling Coils: Provides efficient magnetic coupling and soft-switching, while mitigating losses during energy transfer.

This dual-side architecture ensures contactless, efficient, and fully bidirectional energy flow between the grid and electric vehicle.

B. Control Framework

The control strategy integrates Particle Swarm Optimization (PSO), Sliding Mode Control (SMC), and Phase Shift Modulation (PSM) for robust and adaptive operation:

PSM regulates bidirectional power flow by dynamically adjusting phase shift angles between primary and secondary converters. SMC provides nonlinear robustness, ensuring stable voltage and current regulation under disturbances such as load variation and coil misalignment. PSO optimizes SMC parameters in real time, reducing chattering, minimizing THD, and enhancing overall efficiency. Together, this hybrid control achieves low THD, improved Power Factor Correction (PFC), reduced device stress, and stable synchronization in both operating modes [7-8].

C. Operating Modes

Grid-to-Vehicle (G2V): The grid-side inverter supplies high-frequency AC through the coupling coils, rectified at the EV side to charge the battery. The PSO–SMC–PSM controller ensures smooth charging, high efficiency, and low harmonic distortion.

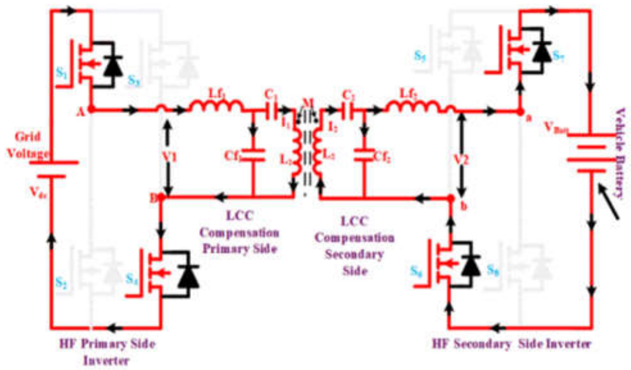

Fig 2: Equivalent circuit of BWPT operation in G2V

Vehicle-to-Grid (V2G): The EV battery discharges through the secondary inverter, inducing AC in the primary coil, which is rectified and fed back to the grid. The proposed control strategy ensures stable grid synchronization, minimized THD, and reliable power injection.

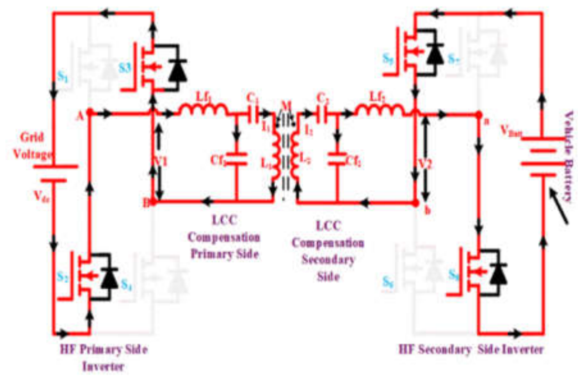

Fig 3: Equivalent circuit of BWPT operation in V2G.

D. Requirement Considerations

The system's functional requirements include enabling bidirectional energy transfer between the grid and electric vehicles (G2V and V2G), along with wireless charging through magnetic coupling. It incorporates a particle swarm optimization (PSO)-based sliding mode controller (SMC) to provide adaptive and robust control, ensuring real-time minimization of total harmonic distortion (THD) and enhancement of power factor correction (PFC). The system is designed to maintain stable operation even under conditions of coil misalignment and load variation. The non-functional requirements focus on achieving high efficiency above 90% during typical operation, ensuring reliability under environmental disturbances, and providing scalability to accommodate different EV power levels. Additionally, the system must comply with electromagnetic interference (EMI), voltage, and thermal safety standards, while offering modularity and maintainability to support long-term deployment and ease of maintenance [9-13].

IV. SIMULATION MODEL

A. MATLAB/Simulink Setup

The proposed Bidirectional Wireless Power Transfer (BWPT) system was modelled and validated in the MATLAB/Simulink environment, which provides a robust platform for analyzing power electronic systems and advanced control algorithms. The simulation framework integrates high-frequency converters, LCC–LCC resonant compensation networks, and magnetic coupling coils to replicate practical wireless charging conditions under both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. In the G2V mode, energy flows from the grid to charge the electric vehicle battery, while in the V2G mode, stored battery energy is transferred back to the grid to support ancillary services. The simulation diagrams for G2V and V2G operation are presented in Figs. 4 and 5. Fig. 6 illustrates the control strategy integrating PSO, SMC, and PSM[14-17].

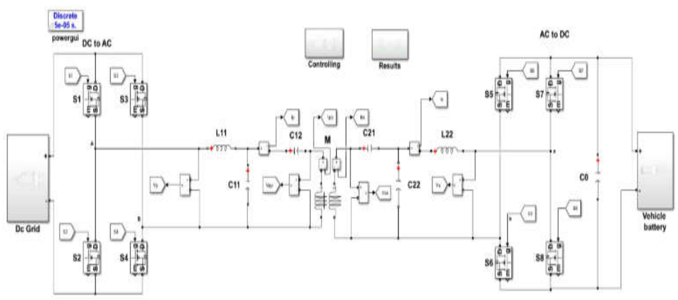

Fig 4: Simulation circuit for Grid-to-Vehicle (G2V)

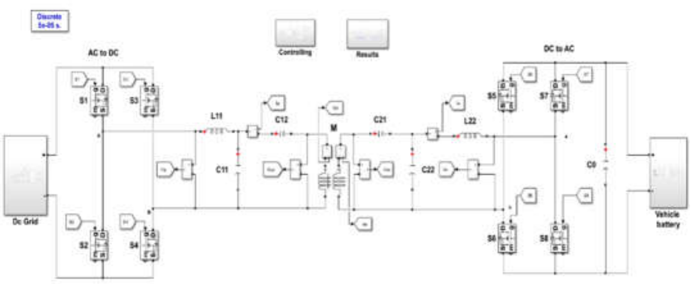

Fig 5: Simulation Diagram for Vehicle-to-Grid (V2G)

To regulate bidirectional power flow, a combined control strategy was implemented, incorporating Particle Swarm Optimization (PSO) for adaptive tuning of controller parameters, Sliding Mode Control (SMC) for nonlinear robustness, and Phase Shift Modulation (PSM) for precise bidirectional power regulation. Custom MATLAB functions were employed to optimize SMC gains using PSO in real time, ensuring accurate adjustment of duty cycles and modulation signals. This hybrid control architecture was

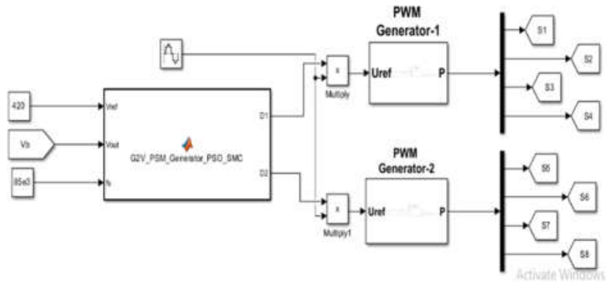

Fig 6: Controlling Diagram with PSO SMC Controlled Phase shift Modulator

tested under practical scenarios such as coil misalignment, coupling coefficient variations, and dynamic load changes, thereby validating the system's stability and efficiency.

B. Parameters Used

The The BWPT system was designed for a rated power capacity of 3.7 kW with a grid input voltage of 325 V at 50 Hz. The resonant compensation network was tuned to operate at high frequency, enabling soft-switching operation that minimizes switching losses and improves overall efficiency. SiC MOSFETs and IGBTs were modelled as switching devices to evaluate performance under realistic operating conditions, combining fast switching capability with high power-handling capacity. Critical circuit parameters included the inductance and capacitance values of the resonant network, the coil turns ratio, the coupling coefficient, and the selected switching frequency. On the vehicle side, the battery was modelled to operate within a voltage range of 220–325 V, with charging and discharging currents determined dynamically by load demand. These parameters were carefully chosen to maximize power transfer efficiency, minimize harmonics, and ensure compliance with grid standards, while maintaining stable operation under both

S: No	Parameters	Symbols	Values
1	Output Power	P_{out}	3.7 kW
2	Input AC voltage	V_{Grid}	325 V
3	Output Converter Voltage	V_{out}	420 V
4	Coupling Co-efficient	K	0.4
5	Switching Frequency	f_s	85 kHz
6	Mutual Inductance	M	46.5μH
7	Capacitor for Primary Side Series Compensation	C_p	31nF
8	Self-Inductance of the Primary Coil	L_P	120 μH
9	Secondary Coil Self Inductance	L_S	120 μH
10	Secondary Side Series Compensation Capacitor	C_S	31nF
11	Capacitance Filter	C_0	30 μF

aligned and misaligned conditions. The overall parameter design and control framework confirm the feasibility of the proposed BWPT system for reliable bidirectional energy transfer in electric vehicle applications.

C. Measurement Setup

To evaluate the effectiveness of the proposed control strategy, several performance metrics were measured within the simulation environment. Total Harmonic Distortion (THD) of both voltage and current waveforms was calculated using Fast Fourier Transform (FFT) analysis tools in MATLAB/Simulink. Power Factor (PF) was measured to assess grid compliance and active power transfer capability. Efficiency was determined by comparing input and output power across both G2V and V2G operations, accounting for switching and conduction losses. In addition, device stress was evaluated by monitoring current and voltage waveforms across MOSFETs and IGBTs, ensuring that the control strategy reduced peak stress and minimized thermal loading. Together, these measurements provided a comprehensive performance evaluation of the proposed BWPT system under varying load conditions, misalignment scenarios, and bidirectional power transfer modes [18-20].

V. RESULTS AND DISCUSSION

Table 8.1: Comparison Table of THD Values in Grid to Vehicle mode

MODES	Grid to Vehicle Mode	
Controller	**PSM**	**PSO - SMC PSM**
Primary side Converter Current	5.74	4.07
Primary side Coil Current	5.66	3.66
Secondary side Converter Current	5.02	3.68
Secondary side Coil Current	5.14	2.86

The THD Comparison Table highlights the Total Harmonic Distortion (THD) values for output currents in both Conventional Phase Shift Modulation (PSM) and advanced PSO-SMC-based PSM controllers during Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. Observing the data, it is evident that the PSO-SMC PSM controller consistently achieves lower THD values across all measurement points, including the primary side converter current, primary side coil current, secondary side converter current, and secondary side coil current.

Table 8.2: Comparison Table of THD Values in Vehicle to Grid mode

For example, in G2V mode, the primary side converter current THD is reduced from 5.74% (PSM) to 4.07% (PSO-SMC PSM), and the secondary side coil current THD drops significantly from 5.14% (PSM) to 2.86% (PSO-SMC PSM).

MODES	Vehicle to Grid Mode	
Controller	**PSM**	**PSO - SMC PSM**
Primary side Converter Current	5.21	3.42
Primary side Coil Current	5.41	3.54

Similarly, in V2G mode, the improvement becomes even more remarkable, with the secondary side converter and coil currents exhibiting far greater reductions than those achieved in G2V mode.

These results confirm that the advanced PSO-SMC-based PSM controller significantly reduces THD, thereby improving power quality and enhancing system performance in both operational modes.

VI. CONCLUSION

In Conclusion, this work proposes integrating a PSO-based Sliding Mode Controller (SMC) into the Bidirectional Wireless Power Transfer (BWPT) system to enhance the performance and reliability of electric vehicle (EV) charging. By using Particle Swarm Optimization (PSO) to fine-tune controller parameters, the system adapts to challenges such as power factor correction, harmonic distortion, and stability. The proposed controller maintains a high-power factor in both Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes, minimizing reactive power and improving energy efficiency. The Sliding Mode Control (SMC) approach increases robustness against load changes, parameter variations, and external disturbances. Fine-tuning the phase shift in Pulse Width Modulation (PWM) through PSO reduces Total Harmonic Distortion (THD), ensuring compliance with grid standards. Simulation results in MATLAB/Simulink confirm significant THD reduction, smoother power flow, lower switching losses, and enhanced system stability. THD is used as a key performance indicator for validating the controller's effectiveness. The optimized control strategy also improves power transfer efficiency and extends the lifespan of system components by reducing unnecessary stress and losses. The approach is scalable to higher power systems and compatible with renewable energy integration, making it suitable for smart grid applications. Future work could incorporate machine learning algorithms to further enhance real-time adaptability.

Overall, the PSO-based SMC offers a flexible, efficient, and resilient solution for managing bidirectional energy flow in EV charging systems. It contributes to achieving sustainable, stable, and intelligent power solutions, supporting the evolving energy landscape driven by electric mobility and distributed renewable generation.

VII. FUTURE ENHANCEMENT

Future work on the proposed BWPT system can focus on several key directions. Hardware implementation and testing using real-time prototypes will validate simulation outcomes and assess EMI, thermal stability, and reliability. Incorporating adaptive frequency control and AI-driven misalignment correction can enhance ZVS/ZCS stability and ensure robust charging under varying conditions. Integration with renewable energy sources and smart grids will enable advanced V2G/V2H applications, while real-time embedded deployment on DSPs or FPGAs can improve controller responsiveness and efficiency. Further, thermal and reliability modelling will help predict device lifespan, and exploring bidirectional EV-to-EV energy sharing can support emergency charging. Compliance with emerging standards such as ISO 15118 and SAE J2954/2 will improve safety and interoperability, while AI-based optimization can enhance predictive fault detection and grid balancing. Finally, techno-economic analysis of cost, efficiency, and carbon savings will guide large-scale commercialization.

IX REFERENCES

[1] M. Venkatesan, N. Rajamanickam, P. Vishnuram, M. Bajaj, V. Blazek, L. Prokop, and S. Misak, ''A Review of compensation topologies and control techniques of bidirectional wireless power transfer systems for electric vehicle applications,'' Energies, vol. 15, no. 20, Oct. 1, 2022, doi: 10.3390/en15207816.

[2] Q. He, Q. Luo, K. Ma, P. Sun, and L. Zhou, ''Analysis and design of a single-stage bridgeless high-frequency resonant AC/AC converter,'' IEEE Trans. Power Electron., vol. 34, no. 1, pp. 700–711, Jan. 2019.

[3] M. Kim, D.-M. Joo, and B. K. Lee, ''Design and control of inductive power transfer system for electric vehicles considering wide variation of output voltage and coupling coefficient,'' IEEE Trans. Power Electron., vol. 34, no. 2, pp. 1197–1208, Feb. 2019, doi: 10.1109/TPEL.2018.2835161.

[4] X. Wang, J. Xu, M. Leng, H. Ma, and S. He, ''A hybrid control strategy of LCC-S compensated WPT system for wide output voltage and ZVS range with minimized reactive current,'' IEEE Trans. Ind. Electron., vol. 68, no. 9, pp. 7908–7920, Sep. 2021, doi: 10.1109/TIE.2020.3013788.

[5] X. Qu, H. Chu, S.-C. Wong, and C. K. Tse, ''An IPT battery charger with near unity power factor and load-independent constant output combating design constraints of input voltage and transformer parameters,'' IEEE Trans. Power Electron., vol. 34, no. 8,pp.7719–7727,Aug.2019, doi: 10.1109/TPEL.2018.2881207.

[6] X. Liu, N. Jin, X. Yang, K. Hashmi, D. Ma, and H. Tang, ''A novel singleswitch phase controlled wireless power transfer system,'' Electronics, vol. 7, no. 11, p. 281, Oct. 2018, doi: 10.3390/electronics7110281.

[7] V. Shevchenko, O. Husev, R. Strzelecki, B. Pakhaliuk, N. Poliakov, and N. Strzelecka, ''Compensation topologies in IPT systems: Standards, requirements, classification, analysis, comparison and application,'' IEEE Access, vol. 7, pp. 120559–120580, 2019.

[8] D. Xu, C. Zhao, and H. Fan, ''A PWM plus phase-shift control bidirectional DC–DC converter,'' IEEE Trans. Power Electron., vol. 19, no. 3, pp. 666–675, May 2004, doi: 10.1109/TPEL.2004.826485.

[9] R. Bosshard, J. W. Kolar, J. Mühlethaler, I. Stevanovic, B. Wunsch, and F. Canales, ''Modeling and η–α -Pareto optimization of inductive power transfer coils for electric vehicles,'' IEEE J. Emerg. Sel. Topics Power Electron., vol. 3, no. 1, pp. 50–64, Mar. 2015, doi: 10.1109/JESTPE.2014.2311302.

[10] R. Bosshard and J. W. Kolar, ''Inductive power transfer for electric vehicle charging: Technical challenges and tradeoffs,'' IEEE Power Electron. Mag., vol. 3, no. 3, pp. 22–30, Sep. 2016, doi: 10.1109/MPEL.2016.2583839.

[11] M. Neath, ''Bidirectional inductive power transfer system: Analysis and control,'' Ph.D. dissertation, Univ. Auckland, Auckland, New Zealand, 2013. [Online]. Available: http://hdl.handle.net/2292/22756

[12] M. Mohammad, O. C. Onar, G.-J. Su, J. Pries, V. P. Galigekere, S. Anwar, E. Asa, J. Wilkins, R. Wiles, C. P. White, and L. E. Seiber, ''Bidirectional LCC–LCC-compensated 20-kW wireless power transfer system for medium-duty vehicle charging,'' IEEE Trans. Transport Electrific., vol. 7, no. 3, pp. 1205–1218, Sep. 2021, doi: 10.1109/TTE.2021.3049138.

[13] S. A. Gorji, H. G. Sahebi, M. Ektesabi, and A. B. Rad, ''Topologies and control schemes of bidirectional DC–DC power converters: An overview,'' IEEE Access, vol. 7,pp.117997–118019,2019, doi: 10.1109/ACCESS.2019.2937239.

[14] V. Juliet, S. Padmanaban, and L. Mihet-Popa, ''Frequency splitting elimination and cross-coupling rejection of wireless power transfer to multiple dynamic receivers,'' Appl. Sci., vol. 8, no. 2, p. 179, Jan. 2018, doi: 10.3390/app8020179.

[15] T. Taipei, X. Xu, A. M. Khambadkone, and R. Oruganti, ''A soft-switched back-to-back Bi-directional DC/DC converter with a FPGA based digital control for automotive applications,'' in Proc. 33rd Annu. Conf. IEEE Ind. Electron. Soc., 2007, pp. 262–267.

[16] K. Colak, E. Asa, M. Bojarski, D. Czarkowski, and O. C. Onar, ''A novel phase-shift control of semibridgeless active rectifier for wireless power transfer,'' IEEE Trans. Power Electron., vol. 30, no. 11, pp. 6288–6297, Nov. 2015, doi: 10.1109/TPEL.2015.2430832.

[17] H. Wu, Y. Lu, T. Mu, and Y. Xing, ''A family of soft-switching DC–DC converters based on a phase-shift-controlled active boost rectifier,'' IEEE Trans. Power Electron., vol. 30, no. 2, pp. 657–667, Feb. 2015, doi: 10.1109/TPEL.2014.2308278.

[18] H. Xiao and S. Xie, ''A ZVS bidirectional DC–DC converter with phase shift plus PWM control scheme,'' IEEE Trans. Power Electron., vol. 23, no. 2, pp. 813–823, Mar. 2008, doi: 10.1109/TPEL.2007.915188.

[19] Y. Yang, Y. Benomar, M. El Baghdadi, O. Hegazy, and J. Van Mierlo, ''Design, modeling and control of a bidirectional wireless power transfer for light-duty vehicles: G2 V and V2G systems,'' in Proc. 19th Eur.

Conf. Power Electron. Appl., Sep. 2017, pp. P1–P12, doi: 10.23919/EPE17ECCEEurope.2017.8099387.

[20] S. Liu, J. Su, and J. Lai, ‘‘Accurate expressions of mutual inductance and their calculation of Archimedean spiral coils,’’ Energies, vol. 12, no. 10, p. 2017, May 2019, doi: 10.3390/en12102017.