



Fuzzy-Adaptive Dual-Side Control of LCC-S Compensated Bidirectional Wireless Power Transfer Systems for Seamless G2V/V2G Transitions Under Coupling and Load Uncertainty

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Abstract

Electric Vehicle (EV) adoption and Vehicle-to-Grid (V2G) technology have created a need for wireless charging systems that can transfer power reliably and efficiently in both directions. However, differences in magnetic coupling, battery voltage and load characteristics create problems regulating power flow, decreasing the efficiency of power transfers, and creating unwanted transients during transitions between Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes. These problems are even more significant in LCC-S compensated bidirectional wireless power transfer (BWPT) systems due to the effects of resonance characteristics and converter interaction on overall dynamic performance. This paper presents an intelligent fuzzy-adaptive dual-side control scheme that will provide smooth power reversals, improved voltage regulation and stable operation in the presence of uncertainty in coupling and loading. The proposed control scheme coordinates the active primary and secondary converters using adaptive phase-shift control, with fuzzy logic continually modifying controller gains based upon power-tracking errors, voltage deviations and changing operating conditions. A detailed MATLAB/Simulink model was developed for a 3.3 kW, 85 kHz LCC-S compensated BWPT system. The model included magnetic coupling variations from 0.15 to 0.35, battery voltages ranging from 250 to 350 V, and load resistance variations of $\pm 20\%$. The system was evaluated during steady-state G2V and V2G operations, commanded power-flow reversals, and simultaneously occurring coupling and load disturbances. Power-tracking error, DC-link voltage deviation, settling time, transient overshoot, transferred power ripple, and end-to-end efficiency were used to assess the system's performance. Comparisons were made between three control strategies: conventional Proportional-Integral (PI) control, fixed-gain dual-side control, and the proposed fuzzy-adaptive control scheme. These comparisons allowed us to determine what advantages are gained by utilizing on-line adaptation. It is anticipated that the proposed fuzzy-adaptive dual-side control strategy will provide increased transient damping, faster transition times between G2V and V2G modes, fewer oscillations in both voltage and power, and more consistent energy-transfer performance throughout the tested operating range. One of the main contributions of this work is the development of a coordinated control framework that incorporates LCC-S resonant compensation with operating-condition-dependent fuzzy adaptation at each end of the wireless link. This addresses some of the limitations of fixed-parameter controllers during bidirectional operation. While this research is primarily simulation-based and does not fully account for electromagnetic interference, thermal aging, communication delays or hardware implementation constraints, it provides a basis for future experimental and hardware-in-the-loop validation studies. From a practical perspective, the proposed strategy could enable more reliable contactless EV charging infrastructure, facilitate flexible participation of parked vehicles in grid-support services, and enhance renewable energy integration.

Keywords: Fuzzy-Adaptive Control; Bidirectional Wireless Power Transfer; LCC-S Compensation; Grid-to-Vehicle (G2V); Vehicle-to-Grid (V2G); Coupling and Load Uncertainty.

I. Introduction:

The rapid growth of electric vehicles (EVs) has created new ways for us to generate, distribute, store and consume electricity. While many people view EVs as an alternative to gas powered cars, they are becoming recognized as a source of flexibility for electric utility companies. EVs' on-board battery systems provide a means of storing excess renewable energy produced during low-demand hours, and if technically feasible and economically viable, returning that stored energy to the grid as needed. This trend is leading to the development of bi-directional charging systems that enable both grid-to-vehicle (G2V) and vehicle-to-grid (V2G) applications. However, enabling both types of applications requires that the charging system be efficient, reliable, user friendly and responsive to the status of the grid and the battery system. The use of Wireless Power Transfer (WPT) is a possible alternative to traditional wired charging since there is no requirement to connect the charging device directly to the electric car. Inductive WPT uses alternating magnetic fields to transmit energy over an air gap from the transmitting coil to the receiving coil. By utilizing this method, it may be able to reduce mechanical wear due to multiple connector insertions, allow for simpler automatic parking-based charging, and increase driver convenience. There have been several reviews that looked into the development of inductive and resonant wireless charging, compensation networks, converter architectures, and how well each type can work for either static or dynamic EV applications [1]–[4]. All together, these studies show that the overall efficiency of a wireless charger depends on the interactions among the magnetic coupling, resonant compensation, semiconductor switching, and closed-loop control rather than just on one part of the system. In addition to providing new opportunities, transitioning from one-way charging to two-way wireless power transfer (BWPT) presents new engineering problems. During G2V operation, electrical energy flows from the electrical utility grid into the vehicle battery; however, during V2G operation, the direction of electrical energy flow is reversed, allowing the vehicle battery to feed power back into the utility grid. Therefore, a single set of charging hardware can act as either an energy consumer or a distributed energy resource. Compensation topologies and control strategies for bidirectional EV charging were studied by Venkatesan et al. [5], who emphasized that the compensation network selection and converter modulation must be analyzed in conjunction with each other. Recent review articles [6]–[8] have broadened the scope of these analyses to encompass grid integration, communications, synchronization and reliability of operation. Even though there are many new technologies that allow for bidirectional wireless charging, there are still some significant differences between the two methods. While it may seem like all we need to do is reverse the flow of electricity, there is actually much more involved. To begin with, each end of the electromagnetic coupling must continue to provide correct voltages, currents, phase angles, and switching frequencies as the energy flow switches directions. If both ends cannot synchronize their operations, then there will be an increase in the amount of reactive energy being produced. In addition to producing excessive reactive energy, an inability to synchronize operations will lead to higher transient voltages, greater stresses placed upon semiconductor devices, and a decrease in system efficiency. It is important to note that the above mentioned issues are especially apparent if the vehicle is not positioned directly above the charging pad or if the battery's operating characteristics change as it is charged/discharged. As such, researchers are currently focusing on developing advanced, adaptable, and coordinated control algorithms that will enable efficient operation under varying operating conditions.

Resonant compensation is necessary when using inductive WPT due to the large leakage inductances and/or air gaps present in the loosely coupled coils which could otherwise restrict the amount of power that could be transferred and require more reactive power. Auxiliary inductors and/or compensation capacitors will need to be added to create appropriate resonant conditions, enhance power transfer capabilities, and minimize the negative effects of overloading the converter. Series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP) compensation methods have been covered extensively in the literature. These methods have been used in various charging scenarios; however, their performance in terms of voltage and current characteristics vary depending upon the load resistance, operating frequency, and coupling coefficient [5], [9]. The use of higher order compensation circuits such as LCL, LCC, LCC-LCC, and LCC-S allow for greater flexibility in system design. Li et al. [10] developed a compensation and tuning technique for a double-sided LCC wireless charging system which allowed them to demonstrate that proper selection of parameters would decrease the sensitivity of the resonant frequency of the system to changes in load and coupling. Double-LCL compensation was investigated by subsequent researchers [11], and parameter selection for LCC-S systems was examined by others [12] to show that resonant network design has a significant impact on obtaining specific types of charging performance. These early works are still applicable today as the compensation network will determine the dynamic behavior of the system that the controller is attempting to regulate. In an LCC-S (inductor-capacitor-capacitor - series) configuration, the transmitter uses an inductor-capacitor-capacitor compensation network, and the receiver uses series compensation. The LCC arrangement at the transmitter allows for shaping the current flow in the transmitter coil and also the input impedance. At the same time, the series compensated receiver has a relatively straightforward resonant structure. A properly adjusted LCC-S network can provide good constant current characteristics, low reactive power circulation, and controlled voltage conversion. Although the topology itself does not ensure that there will be constant efficiency or stable bidirectional operation, it does allow for some level of control over the system's performance based upon the component values chosen, the load, the coupling condition and the operating point. Many studies have investigated ways to enhance the performance of the LCC-S (LCC-Series resonant converter) when subjected to non-ideal operating environments. One such study was conducted by Wang et al., who developed an LCC-S with dual-

coupled compensation and a misalignment-tolerant design [13]. This study demonstrated that the combination of optimizing both the compensation network and coil geometry allowed the converter to maintain suitable output characteristics throughout a specified displacement range. Additionally, Wang et al. [14] implemented a combination of receiver-side switched-controlled capacitance and a semi-active rectifier to control the converter's output voltage during variations in coupling and load conditions. To demonstrate this capability, Wang et al. built a 3 kW experimental prototype that illustrated how the use of additional control freedom could provide the ability to adjust the resonant operating condition of the converter as well. The results of these studies are significant since they illustrate that the behavior of the compensation network can be enhanced via active adjustments versus solely relying on fixed passive components. Further advances are being made in three-phase LCC-S systems as a result of using a converter design and two sides of closed loop control to allow for a broader range of operating conditions [15]. Additionally, there is a better understanding of how to model the small signals associated with multi-phase LCC-S inductive transfer systems [16], which will provide a more solid theoretical foundation for developing controllers that exhibit specific dynamic properties. More recent work has explored LCC-S applications in conjunction with on-board charging (and discharging), bidirectional operation, and constant-current/constant-voltage characteristics [17, 18]. The findings of these works support the use of the LCC-S topology in real world applications, but also emphasize the necessity to consider the non-linear, operating point dependent nature of this type of system. Gu [19] provided a very good example of how to make your own study relevant to another research in the field. He studied bidirectional wireless charging with an LCC-S compensation network and vehicle side DC-DC regulation. His study showed that it was possible to achieve stable bidirectional charging and discharging with varying coupling and voltage. While the fact that there is a working bidirectional LCC-S architecture does not mean that we have found the most effective way to manage the two active converters when they need to quickly change direction of power flow; this means that we still need to continue looking into different types of controller architectures that will allow us to simultaneously control transient behavior, manage uncertainties and keep efficiency high.

One of the biggest problems with wireless EV charging is that the amount of variability in the magnetic coupling between the transmitting coil and receiving coil. The coupling coefficient depends on coil geometry, distance apart, lateral displacement, angular misalignment, magnetic shielding, and other surrounding materials. While automated parking assistance may help to reduce some of these variables, there will always be variability due to vehicle positioning errors, suspension movements, and differences among various types of vehicles. Viqar et al. [20] studied how misalignment and compensation topologies affected the performance of the system using models, simulations, and experimental hardware results; demonstrating the need to consider non-ideal positioning of the coils. Additional researchers have also looked into adaptive coil and compensation design [21], variable structure compensation [22], and matching of coupling coefficients [23], in order to increase power stability across broad ranges of operation. All of these studies demonstrate that it is not always possible to eliminate magnetic uncertainties solely by aligning the coils mechanically or with fixed compensation. Load uncertainty is a related problem. The resistance of an electric vehicle (EV) battery is not static. Instead, its terminal voltage, equivalent impedance and allowed charging and discharging currents change with state of charge (SOC), temperature, chemistry of the battery, and the constraints imposed by the battery management system. Also, when transitioning from G2V to V2G, the control objective is different because the controller must regulate energy flows in opposite directions under varying current and voltage limitations. The way that all three of the above described uncertainty types interact is extremely important. For example, if there is a decrease in coupling, you will have to increase your converter excitation so as to transfer as much power as before; however, at the same time, if the battery-voltage changes, then this changes the effective conversion ratio. On one hand, if the controller responds too fast to the above changes, you could get a high current/voltage overshoot which would lead to additional losses and increased stress on the components. On the other hand, if the controller responds too slowly, then the charger will either not be able to follow the requested power profile, or will remain disturbed for long periods of time after reversing power flow. Thus, the main issue is how to achieve stable, efficient and precise control over bidirectional power flow without using static operating conditions, and without developing overly complex control strategies.

The simple implementation, low computational requirements, and familiarity of the industry with conventional proportional-integral (PI) and proportional-integral-derivative (PID) controllers make them popular choices for use within power-electronic systems. While the operating conditions of a system remain near the nominal design values, well-tuned linear controllers can provide acceptable tracking and disturbance rejection. However, as the dynamic characteristics of the plant change dramatically due to variations in coupling, the non-linear switching behavior of the system, and/or changes in power flow, fixed-gain controllers can lose some of their effectiveness. Bidirectional wireless power transfer control is becoming more dependent upon the use of modulation methods to directly affect converter voltage and phase relationships. A variety of single-phase-shift, dual-phase-shift, and other more complex modulation techniques are being studied as a means of controlling power transferred, limiting reactive current and enhancing soft-switching capabilities. An optimized power-efficiency coordinated approach [24] illustrated the benefit of coordinating converter operations and controlling phase relationships during bidirectional charging and discharging cycles. These types of studies establish a fundamental base for developing coordinated controls since they demonstrate how power

control and efficiency are interrelated rather than independent goals. The 2024 simulation and experimental study on dual-phase-shift PWM (DP-PWM) used with BWPT [25] reported a simulated transfer efficiency of 94.4% and an experimental efficiency of 90.1% for a 3.7 kW system operating at 85 kHz. The studies showed that coordinate modulation is feasible in bidirectional EV charging. However, those reported efficiencies apply only to the specific experimental architecture studied; they cannot be used to generalize performance for all LCC-S systems. Furthermore, while the efficiency of a system can be high under steady-state conditions, this does not guarantee good transient performance during changes in coupling, load, and commanded power direction. Another approach to controlling resonant operation is through optimizing the resonant operation itself. In addition to a dual-phase-shift control strategy with switched-controlled capacitance (SCC) [26], which provided both efficient control and soft-switching regulation for a 6.6 kW experimental prototype, newer studies have examined triple-phase-ratio-shift modulation for bidirectional wireless power transmission [27]. This demonstrates how there continues to be new developments in converter modulation strategies that provide solutions to power factor correction, reducing switching losses and improving converter complexity. While these methods increase the number of options for controlling resonant operation, they are dependent upon choosing the right parameters and managing the interaction between converter side control variables. A second limitation of dual-side control is that it results in a trade-off between the simplicity of single-side control (i.e., reduced communication requirements, simpler implementation) and the increased authority that comes with dual-side control. While dual-side control can allow for more control over the operating point, the introduction of multiple control variables also allows for competing control actions. For example, if two independent controllers are acting on the same converter and each attempt to adjust converter excitation based upon the same power error, then there could be too much circulating current created, or oscillations could develop. Therefore, in order to properly implement dual-side control, each converter must have a clearly defined role, such as one being responsible for regulating the DC link voltage, while the other is responsible for tracking power or regulating battery current. The previous results show that conventional modulation methods give you the ability to control how much energy flows through your system. However, in order to make sure that your system works well under many different conditions, you might need to use adaptive supervisory control.

Growing interest in intelligent control is due to the fact that many wireless charging systems have both non-linear characteristics and variation in parameters that cannot be easily accommodated by using only one fixed linear model. Therefore, fuzzy logic control is especially useful for translating measured operating errors into rules-based control adjustments without needing to develop an accurate analytical representation of all non-linear effects. The fuzzy controller evaluates variables (i.e. tracking error, rate of change of error) and uses linguistic rules to determine the correct corrective actions based upon membership functions and the inference engine. The adaptive version of the fuzzy controller can adjust gain values for the controller, modulation parameters for the controller or reference points for the supervisor based on the operating condition. Therefore, this type of architecture provides a good balance between traditional feedback controls and more computationally complex nonlinear optimizations. Kiyani et al. [28] studied a fuzzy supervisory strategy for wireless power transfer (WPT) systems, showing how relevant fuzzy-based regulation is to wireless energy transfer. This study adds to the larger body of evidence supporting the use of intelligent supervisory control in order to provide increased flexibility in operation. It should be noted that the application of fuzzy logic to a WPT system is not an original contribution; rather, what is more significant is the development of a methodology for design of a fuzzy adaptive controller that can coordinate both converters when there is bi-directional operation and that includes consideration of resonant constraints and uncertainty. This proposed fuzzy-adaptive dual side approach is a solution to the problem of adjusting the control response while using a conventional converter modulation scheme. For example, the controller can be used to adjust the gains of both primary and secondary side regulators through the utilization of normalized power error, dc-link voltage deviation, and their respective rates of change. It would also be possible to incorporate scheduling based on estimated coupling or battery voltage when these parameters can be either measured or estimated accurately. This approach offers a number of benefits. When operating in steady state conditions, the controller may apply softer gain settings to limit excessive oscillations and switches. A fuzzy supervisory system can provide temporary increases in gain when there are large changes in power reference or mode transitions. In addition, when subjected to disturbance inputs that create coupling between variables, an adaptive mechanism can adjust to variations in plant sensitivity while protecting against exceeding current and/or voltage limits. Nonetheless, fuzzy control does not automatically imply a robust and stable system. The membership functions, the rule base, the scaling factors, and the adaptive limiters must all be chosen based on systematic methods. If the fuzzy rules are poorly chosen, they can cause an increase in noise, produce multiple interacting control loops, and/or lead to poor system stability at the zero-power operating point. Therefore, a valid fuzzy-adaptive BWPT study should include: sensitivity analysis, controller gain bound analysis, and comparisons to properly tuned conventional controllers.

At this point, there is still much to be done in regards to the integration of three distinct research areas - compensation design, bidirectional converter modulation and intelligent control. First, most compensation network studies focus on steady state properties, alignment tolerances and constant current and constant voltage operation. While these are critical performance criteria for a compensation network, they do not adequately represent the dynamic response of a

bidirectional charger as the power reference transitions through zero and changes from positive to negative. Second, in many cases control studies will focus on optimizing only one key objective of the system (e.g. output voltage regulation; efficiency optimization; power factor correction). However, during practical G2V/V2G operation of the system, all of the above mentioned objectives must be optimized simultaneously while also taking into account the transient response of the system, converter current limits, battery limitations, and grid requirements. Therefore, a control strategy designed to minimize steady state loss is not necessarily the best strategy to provide fast and safe power reversal. Thirdly, the relationship between primary and secondary control loops is not typically defined clearly. To coordinate these systems, you must install more than two separate controls. The roles of the controls, the way they generate references, when they operate, and how they react to disturbances should all be coordinated so that they do not conflict with each other. Fourth, uncertainty testing has traditionally been performed in isolation. While a controller might function correctly under a disturbance caused by the coupling, while operating at a fixed level of load, or under a load change with a nominal coupling, the same controller will likely behave differently if both types of disturbance are present simultaneously, particularly during a transition from one mode to another. Therefore, performing simultaneous uncertainty testing is necessary to provide evidence that the controller is truly robust. Finally, there are still a number of communication and implementation limitations. Ye and Parspour [29] have studied how wireless power transfer (WPT) and near field communication (NFC) can be integrated together to allow for cooperative operations based on information exchange. In addition, recent studies have looked at the larger picture of power electronics, control, communication and cybersecurity with respect to grid-interactive wireless charging [8]. These studies indicate that in practice dual side coordination will be limited by sensing, synchronization, communication delay and fault performance; it will not be based upon the assumption that each side is receiving an instant stream of perfect data. The remaining research issue may then be summarized as follows: How will an LCC-S compensated bidirectional wireless charging system be able to coordinate both active converters so as to provide a transition from G2V/V2G that is as smooth as possible, while at the same time providing accurate tracking of power transfer; providing reasonable transient response characteristics for both voltage and current; and operating efficiently when subjected to uncertainty in both coupling and load conditions? This is the specific problem addressed by the proposed research.

This work presents a new dual-side control approach for a LCC-S compensated BWPT system. It uses an active grid-side converter, an LCC-S resonant wireless link, an active vehicle-side converter, and dual-side coordinated feedback control. To evaluate the proposed system, we conducted simulations with a nominal power rating of 3.3 kW, a nominal switching frequency of 85 kHz, coupling coefficient ranges from 0.15 to 0.35, battery voltage ranges from 250 to 350 V, and load variations of plus or minus twenty percent. These simulation parameters represent the conditions used to test the proposed system, not historical performance data. Control structures are used to differentiate between faster converter control loops and slower adaptive supervisory decision making loops. The phase-shift modulated converter regulates the effective excitation of the resonant circuit and the direction of power transfer. Supervisory fuzzy logic changes certain controller gain values or control references based on tracking error and/or operating condition changes. During G2V (Generation to Vehicle) operation, the controller manages the amount of power being charged to the battery while keeping the DC-link voltage and resonant network within safe operating limits. If the user requests V2G (Vehicle to Grid) operation, the controller's reference signal will reverse direction via a controlled transition. The strategy suggested in this paper does not allow for sudden, uncontrolled changes in the modulation of the converter; instead, it provides a defined power trajectory and coordinated responses from the converters to reduce transient stresses. The main objectives of this study were to develop four distinct types of controls: (1) A dual-side control system developed for bidirectional LCC-S operations; (2) An on-line adaptation technique based on fuzzy logic to allow the controller to respond better to changes in the environment or load conditions; (3) A transition management method that allows the controller to limit the effect of power reversals on the system, yet still meet the systems electrical limitations; and (4) A comparative simulation platform that will enable us to compare our proposed controller with traditional proportional-integral (PI) controllers and static dual-side controls during similar operating conditions. The evaluation of performance will include measuring the settling time, peak power over-shoot, DC-link voltage deviations, power tracking error, current stresses, and the overall end-to-end efficiency. Additionally, the focus of the evaluation will be placed on assessing the simultaneous uncertainty and power reversals, instead of solely evaluating the steady-state efficiencies. The proposed scientific contribution will be the simultaneous application of fuzzy logic, LCC-S compensation and phase-shift modulation as well as an evaluation of these techniques in a bi-directional operating environment. It will not be the development of any one of these techniques individually. Therefore, the scientific contribution will be established by demonstrating how the combination of the techniques outperforms other methods in terms of performance and efficiency. The proposed framework has practical value as well. Contactless bidirectional charging will enable automated charging stations, eliminate the need for manual connection of cables, and allow EVs to participate in distributed energy management. If permitted by local electricity market rules, grid interconnection requirements, and battery management system (BMS) operations, V2G capabilities may contribute to managing peak demand and integrating renewable resources into the grid. It is important to note that the environmental and economic benefits of V2G are dependent upon the type of electricity generated, the rate at which batteries degrade over time, the efficiency losses during charging and discharging processes, and the schedules

under which the vehicle is operated. Therefore, it is not possible to determine whether or not there are environmental or economic advantages based solely on the performance of the V2G controller.

The remainder of this paper is organized as follows. Section II describes the LCC-S bidirectional power stage; Section III presents the fuzzy-adaptive dual-side controller; Section IV details the simulation model and comparison methodology; Section V examines the illustrated operating scenarios; Section VI discusses implementation and validation; and Section VII concludes the study.

II. Configuration of the proposed LCC-S compensated bidirectional wireless power transfer system with fuzzy-adaptive dual-side control.

Figure 1 illustrates the proposed fuzzy-adaptive dual-side controlled LCC-S compensated bidirectional wireless power transfer (BWPT) system for electric vehicle (EV) charging and grid-support applications. The architecture integrates a bidirectional grid-interface converter, DC-link capacitor, primary high-frequency inverter, LCC resonant compensation network, magnetically coupled coils, secondary series compensation, and vehicle-side active converter. The system is designed to support grid-to-vehicle (G2V) charging and vehicle-to-grid (V2G) energy transfer while maintaining stable operation under variations in magnetic coupling, battery voltage, and electrical loading. The primary LCC compensation network consists of a compensation inductor, series capacitor, and parallel capacitor connected to the transmitting coil. This configuration compensates for the reactive characteristics of the loosely coupled magnetic link and provides flexibility in controlling resonant current and reactive power. The secondary series compensation capacitor offsets the receiving coil's inductive reactance while reducing the number of vehicle-side passive components. Both compensation networks are designed for a nominal switching frequency of 85 kHz and a rated transferred power of 3.3 kW. During G2V operation, electrical energy flows from the utility grid through the grid-side converter and primary resonant network to the vehicle-side converter and EV battery. During V2G operation, the power-flow direction is reversed, allowing stored battery energy to be delivered to the utility grid. Coordinated converter modulation enables bidirectional operation, while a supervised power-reference transition progressively reduces the commanded power toward zero before increasing it in the opposite direction. This strategy is intended to limit transient oscillations, DC-link voltage deviations, and excessive current stress during operating-mode transitions. The proposed fuzzy-adaptive control architecture employs coordinated grid-side and vehicle-side controllers to regulate transferred power, DC-link voltage, and battery charging or discharging current. Fuzzy inference mechanisms adjust the proportional and integral gains according to tracking errors and their rates of change, providing adaptive regulation under changing operating conditions. A communication and synchronization interface coordinates power references, operating modes, and converter modulation commands while supervisory protection enforces the relevant electrical limits. The system is evaluated over coupling coefficients of 0.15–0.35, battery voltages of 250–350 V, and equivalent load variations of $\pm 20\%$. MATLAB/Simulink simulations are intended to compare the proposed controller with conventional PI and fixed-gain dual-side PI strategies using power-tracking accuracy, settling time, DC-link voltage regulation, resonant-current stress, and energy-transfer efficiency. The proposed architecture provides a simulation-based platform for investigating adaptive bidirectional wireless EV charging, with experimental validation required to establish its practical performance.

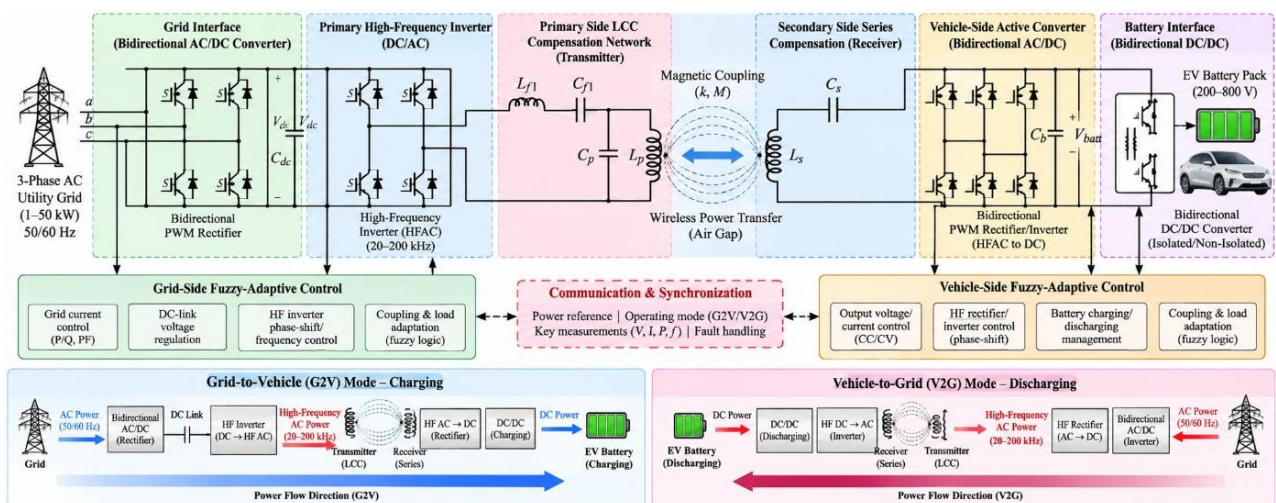


Fig. 1: Proposed configuration of the fuzzy-adaptive dual-side controlled LCC-S compensated bidirectional wireless power transfer system, illustrating grid- and vehicle-side power conversion, primary LCC and secondary series compensation networks, magnetic coupling, coordinated control, and G2V/V2G power-flow operation under coupling and load uncertainty.

III. Proposed Fuzzy-Adaptive Dual-Side Control Strategy for Bidirectional Wireless Power Transfer.

Figure 2 illustrates the proposed fuzzy-adaptive dual-side control architecture for the LCC-S compensated bidirectional wireless power transfer (BWPT) system. The architecture integrates grid-side and vehicle-side adaptive PI controllers, fuzzy inference mechanisms, communication-based coordination, and supervisory power-flow management to support grid-to-vehicle (G2V) and vehicle-to-grid (V2G) operation. Designed for a 3.3-kW, 85-kHz wireless charging system, the proposed strategy aims to improve power regulation, transient response, and operational stability under variations in magnetic coupling, battery voltage, and electrical loading. The grid-side controller regulates the DC-link voltage, grid current, and power exchange through the bidirectional AC/DC converter and primary high-frequency inverter. During G2V operation, the grid interface operates as an active rectifier, whereas during V2G operation, it functions as an inverter. The vehicle-side controller manages transferred power, battery charging and discharging current, and vehicle-side DC-link voltage through the secondary active converter and battery interface. Both controllers use measured feedback signals to determine regulation errors and generate appropriate converter modulation commands. The fuzzy-adaptive mechanism continuously evaluates the control error and its rate of change to adjust the proportional and integral gains within predefined limits. Larger deviations may require stronger corrective action, while smaller errors permit less aggressive regulation to reduce unnecessary oscillations. Unlike conventional fixed-gain PI controllers, this approach allows the regulation characteristics to respond to changing operating conditions without modifying the underlying converter modulation strategy. Communication and coordination between the two controllers ensure consistent power references, operating-mode commands, and converter actions. A supervisory transition manager controls G2V/V2G reversal by gradually reducing the transferred-power reference toward zero before increasing it in the opposite direction. During this process, the controller monitors DC-link voltage, battery current, resonant current, and transferred power to limit transient disturbances and enforce electrical protection requirements. The proposed architecture is designed to accommodate coupling coefficients between 0.15 and 0.35, battery voltages from 250 to 350 V, and load variations of $\pm 20\%$. When operating conditions exceed the converter or battery limits, supervisory protection takes priority over power tracking, allowing the requested power to be reduced when necessary. The control strategy will be evaluated in MATLAB/Simulink against conventional PI and fixed-gain dual-side PI controllers using power-tracking accuracy, settling time, voltage deviation, current stress, and energy-transfer efficiency. This comparison will establish whether fuzzy-adaptive gain adjustment provides measurable improvements beyond conventional dual-side coordination.

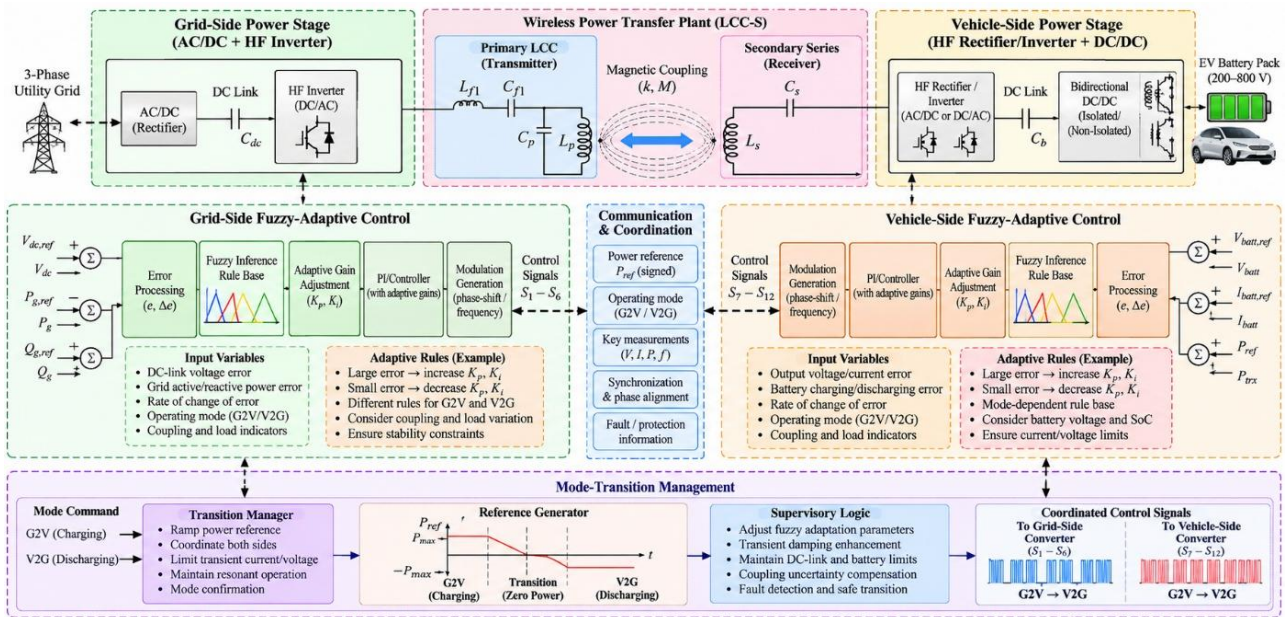


Fig. 2: Proposed fuzzy-adaptive dual-side control architecture for the LCC-S compensated bidirectional wireless power transfer system, illustrating coordinated grid- and vehicle-side control, fuzzy inference mechanisms, adaptive PI gain adjustment, phase-shift modulation, communication and synchronization, and supervised G2V/V2G mode-transition management under magnetic coupling and load uncertainties.

Figure 3 demonstrates the operational steps of the suggested fuzzy-adaptive dual-side control scheme, showing the relationship between real-time data acquisition, adaptive control, and the transition between G2V and V2G modes. The first step in implementing the algorithm is setting up all the initial system parameters, fuzzy logic rules, controller parameters, and protection thresholds. Once these initializations have been completed, real-time measurements can be obtained from the grid-side converter, the wireless power transfer link, and the vehicle-side converter so as to determine

the current state of operation and select the correct power transfer mode. The safety assessment results in the supervisory controller creating the required power reference based upon whether there is a G2V or V2G operation request. When a mode reversal takes place, a ramp of controlled power reference will be used to make the transition from one zero power region to another as smoothly as possible. Both vehicle side and grid side fuzzy inference systems will process the measured control error and rate of change of control error as inputs and create output PI controller gain adjustments based upon current system operating conditions. Coordinated modulation command signals will be created for both converters while being constrained by the resonant network and electrical operating limits. The continuous feedback loop of the algorithm monitors its performance in terms of power-tracking accuracy, voltage regulation, changes in the coupling of the system, and any disturbance caused by changes in the load. If an unusual condition is identified, then the protective action taken will either limit the amount of power being transferred from one side of the system to another, or initiate a controlled shut down. If nothing unusual is observed, then the control cycle will continue to take new measurements and adapt to those measurements as necessary. This type of structured operation is a good way to implement the proposed MATLAB/Simulink model, and provides a foundation for assessing how smoothly the transition occurs, how well the system can reject disturbances, and how robust the control scheme is when operating at different points on the operating curve.

IV. MATLAB/Simulink Implementation, System Parameters, and Comparative Evaluation Methodology.

The proposed fuzzy-adaptive dual side control strategy has been evaluated by using a complete simulation environment that was created with MATLAB/Simulink and uses the Simscape Electrical toolset to model the power electronic converters, resonant compensation networks, and magnetically coupled coil. The simulation environment will be used to simulate both the electrical behavior and the dynamic relationships of an LCC-S compensated bidirectional wireless power transfer (BWPT) system in both Grid to Vehicle (G2V) and Vehicle to Grid (V2G) modes of operation. The simulation model shown in Fig. 1 is composed of: a three-phase utility grid; a bidirectional grid-interface converter; a DC-link capacitor; a primary high-frequency inverter; an LCC compensation network; a set of magnetic-coupling transmitting/receiving coils; a secondary series compensation network; a vehicle-side active converter; a bidirectional DC/DC converter; and an equivalent EV battery model. All of these power-conversion steps are modeled through the use of controllable semiconductor switching components, enabling the examination of switching characteristics, transient current responses, and interactions among the converters when operated bidirectionally. In addition to modeling each coil with its self-inductance and equivalent series resistance, the primary and secondary coils are also modeled with their mutual inductance. A variety of magnetic coupling coefficients are used to represent varying levels of coil alignment and separation distances. Resonance compensation components are chosen to achieve the desired operating behavior at the nominal switching frequency of 85 kHz. Each component value must be determined using the LCC-S resonant design procedure and verified through frequency response and steady-state simulations prior to dynamic controller testing. An equivalent electrical model of the battery that can reproduce the change in terminal voltage and current during both charge and discharge cycles, was used to represent the battery. To determine how well the controller would perform under various operating conditions, the battery voltage was varied from 250 to 350 V. A bidirectional DC/DC converter regulated the battery-side current and voltage based on the operating mode selected by the user and any limitations on the battery. The suggested fuzzy adaptive control system has been developed with individual control systems for each of the grid-side and vehicle-side converter. Both control systems contain components that will process measured variables, create references, use PI control, apply fuzzy logic to make decisions, adaptively adjust gains based on current operating conditions, and generate pulses through pulse width modulation (PWM). A master controller will coordinate the actions of both control systems as well as transition between grid-to-vehicle (G2V) and vehicle-to-grid (V2G) modes of operation. Fuzzy Inference Systems (FIS) will utilize selected tracking error(s), as well as the rate of change of those tracking errors, in order to estimate what would be appropriate adjustments to the Proportional-Integral (PI) Controller's gains.

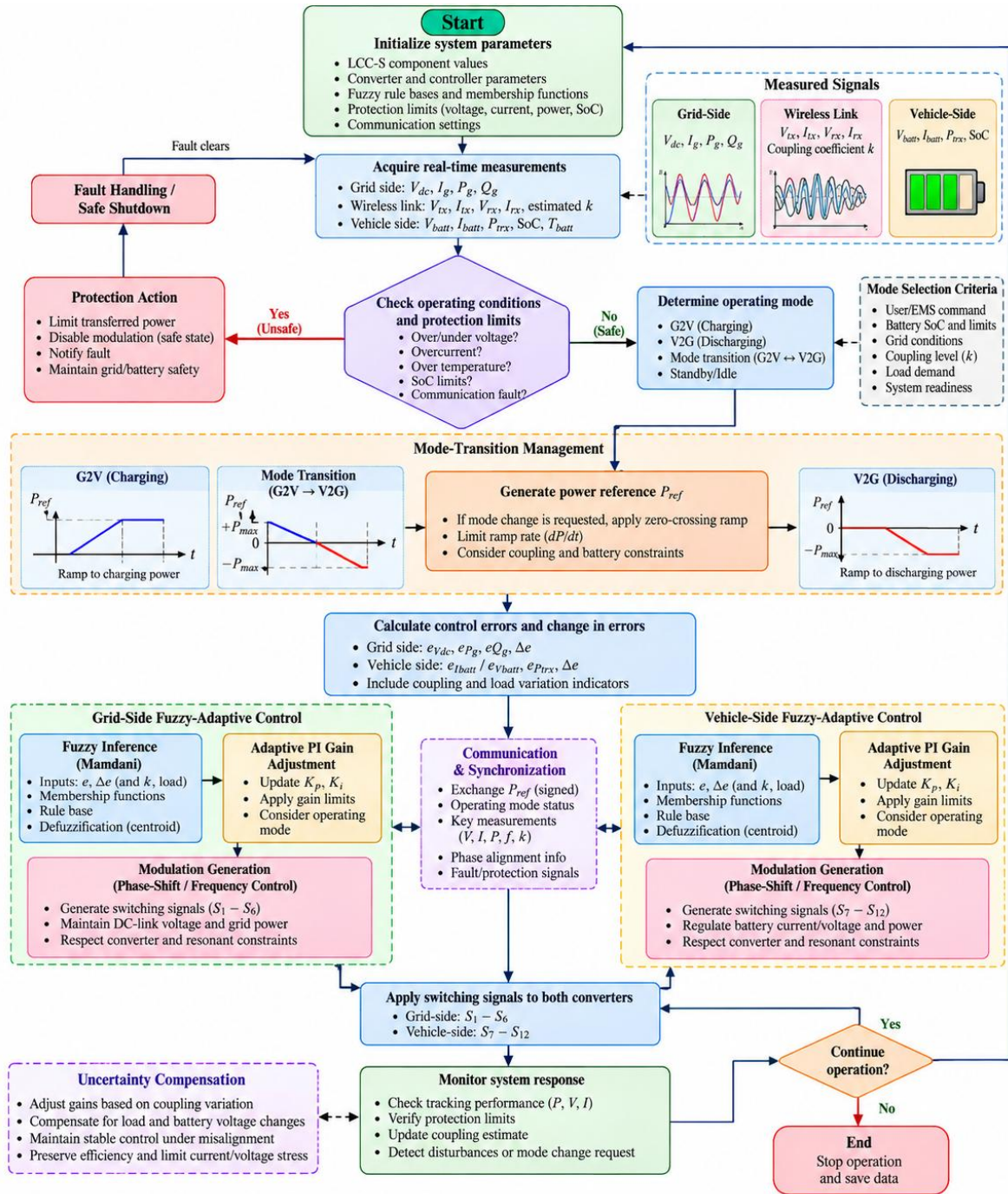


Fig. 3: Flowchart of the proposed fuzzy-adaptive dual-side control algorithm for LCC-S compensated bidirectional wireless power transfer, illustrating measurement acquisition, operating-mode identification, fuzzy inference, adaptive PI gain adjustment, coordinated converter modulation, G2V/V2G power-reference transition, uncertainty compensation, and protection management.

Those adjusted gains will be limited to a specific range of operation in order to avoid generating too much control signal. After the adjustments to the PI Controller's gains have been made, the Modulation Block(s) will then create the switching signals necessary to control the amount of power being transferred from one side of the converter to another, and keep the converter operating in a stable manner. The simulation model has been structured so that it permits a direct evaluation of the difference in performance of three types of control methods: (1) conventional PI control, (2) fixed-gain dual-side control, and (3) the new fuzzy-adaptive dual-side control. All these types of controls use the same basic power-circuit parameter values. Therefore, the effect that each control method has on system response can be evaluated separately from the effects that are due to differences in converter rating, compensation network design, etc. Table I provides a summary of the key parameters and performance characteristics of the system and simulation. The proposed system has a nominal

rating for power transfer capability of 3.3 kW, and it uses a high-frequency switching frequency of 85 kHz, which falls within the typical operating frequency band for most wireless electric vehicle (EV) charging systems. The nominal coupling coefficient was set at 0.25, and the study of the coupling coefficient's variation (from 0.15 to 0.35) represented the change in magnetic coupling that occurred when the position of the vehicle and/or alignment of the coils changed. The battery voltage varied from 250V up to 350V, and the load resistance equivalent was varied by $\pm 20\%$ compared to its nominal value. The nominal grid-side DC-link voltage of 400 V is set as the starting point for design, but will need to be verified with respect to the selected grid-interface topology and modulation constraints. The simulation will include a three-phase utility supply and two-way power-electronic converter stages that can support both charging and discharging. The inductances and capacitances of the compensation network are determined by the chosen coil parameters, nominal resonant frequency and required voltage and current characteristics. The final value for each component must be such that it satisfies the required resonant condition and does not exceed the maximum allowable stress on any single component during operation over the entire range of investigated coupling and loading. This model includes other features such as current and voltage protection limits, converter switching limits, and a controlled power-reference ramp for when the operating mode changes. These additional features are designed to avoid unrealistic switching commands and to provide an accurate representation of how the control strategies will operate under realistic operating conditions.

TABLE I: Proposed System Specifications and Matlab/Simulink Simulation Parameters

Parameter	Value
A. Electrical system specifications	
Rated bidirectional power	3.3 kW
Grid voltage (line-to-line RMS)	400 V
Grid frequency	50 Hz
Grid-side DC-link voltage	700 V
Vehicle-side DC-link voltage	400 V
High-frequency switching frequency	85 kHz
Grid-interface switching frequency	10 kHz
Battery DC/DC switching frequency	20 kHz
Grid-side DC-link capacitance	2,200 μ F
Vehicle-side DC-link capacitance	1,000 μ F
Grid-interface filter inductance (per phase)	3 mH
Grid-interface filter resistance (per phase)	0.1 Ω
B. Wireless coupling and LCC-S compensation	
Nominal coupling coefficient	0.25
Coupling coefficient range	0.15–0.35
Primary transmitting-coil inductance	200 μ H
Secondary receiving-coil inductance	200 μ H
Nominal mutual inductance	50 μ H
Primary compensation inductor	50 μ H
Primary series compensation capacitor	70.1 nF
Primary parallel compensation capacitor	23.4 nF
Secondary series compensation capacitor	17.5 nF
Primary-coil equivalent resistance	0.15 Ω
Secondary-coil equivalent resistance	0.15 Ω
Compensation-inductor equivalent resistance	0.05 Ω
Nominal coil separation	150 mm
C. Battery and load parameters	
Battery nominal voltage	300 V

Battery operating voltage range	250–350 V
Battery nominal capacity	60 Ah
Initial battery state of charge	50%
Permissible SOC range	20–90%
Nominal battery internal resistance	0.10 Ω
Battery internal resistance variation	$\pm 20\%$
Nominal equivalent load resistance	27.3 Ω
Equivalent load resistance variation	$\pm 20\%$
Rated battery charging/discharging current	11 A at 300 V
Battery current protection limit	± 15 A
D. Power converter and control parameters	
Primary high-frequency converter	Active full-bridge
Secondary high-frequency converter	Active full-bridge
Grid-interface converter	Three-phase bidirectional PWM
Battery-interface converter	Bidirectional buck–boost
Modulation strategy	Coordinated phase-shift control
Nominal phase-shift angle	30° initial setting
Maximum phase-shift magnitude	90°
Conventional PI proportional gain	0.5 initial normalized value
Conventional PI integral gain	100 s ⁻¹ initial normalized value
Adaptive proportional gain range	0.2–1.2
Adaptive integral gain range	50–250 s ⁻¹
Fuzzy inference method	Mamdani
Membership functions per input	5
Fuzzy linguistic variables	NL, NS, ZE, PS, PL
Fuzzy rule-base size	25 rules per two-input FIS
Defuzzification method	Centroid
Controller sampling period	100 μ s
Fuzzy adaptation update period	1 ms
Power-reference ramp rate	3.3 kW/s
Zero-power transition threshold	± 50 W
DC-link voltage tolerance	$\pm 5\%$
E. Simulation and testing specifications	
Numerical solver	Fixed-step discrete
Electrical simulation time step	0.1 μ s
Total simulation duration	6 s per transition test
Nominal G2V power reference	+3.3 kW
Nominal V2G power reference	–3.3 kW
G2V-to-V2G command time	2 s
V2G-to-G2V command time	4 s
Coupling disturbance test	0.25 $\rightarrow$ 0.15 $\rightarrow$ 0.35
Battery voltage test	250, 300, 350 V
Load disturbance test	–20%, nominal, +20%
Comparative controller 1	Conventional fixed-gain PI

Comparative controller 2	Fixed-gain dual-side PI
Comparative controller 3	Proposed fuzzy-adaptive dual-side PI
Evaluation metrics	Tracking error, overshoot, settling time, voltage deviation, current stress, efficiency

To assess how well the proposed fuzzy-adaptive scheme works, we use three different types of controllers for comparison. One of those is a traditional fixed-gain PI controller, which will be our "standard" control approach. We have designed this controller with fixed gain values that work well in a variety of nominal operation conditions (i.e. nominal coupling and load) and we will use these same gain settings during all of our simulation runs. A second setup utilizes coordinated two-sided control with constant pi gains. With this setup, the vehicle-side and grid-side controllers share necessary operating data and synchronize their modulation signals. However, in contrast to the first setup, no online gain adjustments are performed. This setup is especially significant since it distinguishes between the performance benefits that result from the use of coordinated dual-side control and those resulting from the application of fuzzy adaptation. In the third configuration, we have used our proposed fuzzy adaptive dual sided control method. Each of the converter controls uses a fuzzy inference mechanism to vary certain PI gains based on the operating error, how fast the error is changing, and other uncertainties that may affect the converter's performance. Our adaptive gains are limited by our predefined parameters. Our supervisory controller will coordinate each converter's response when there is a change in the direction of power flow. All three of the proposed control strategies will be evaluated based on the exact same converter rating, resonant component selection, magnetic coupling profile, battery operating condition, and desired power trajectory. Additionally, the same protection limits and numerical simulation parameters will be utilized. To ensure that each of the proposed control strategies is compared to other properly configured baseline control strategies, controller tuning was performed in a systematic manner. The proposed controller offers increased flexibility when working conditions vary from their standard operating conditions. The effectiveness of the controller is measured by the performance of the simulation results rather than assumed based upon the application of fuzzy logic only.

The comparative analysis will use a number of operational conditions (or scenarios) designed to assess steady state performance, transient response, and robustness against uncertainty. 1) Forward-Transfer Steady State Charging: In this mode, the system transfers power in the forward direction (i.e., from the utility grid to the EV battery) by transferring energy from the utility grid to the EV battery. During operation in this mode, the charging power reference remains constant at its designated level while the controller adjusts the battery current, DC-link voltage, and power transferred. This mode serves as a basis for establishing typical operating conditions and can be used to compare against other modes for tracking error, current ripples and efficiencies. 2) Steady-State V2G Discharging: This operating condition is characterized by a flow of energy in the opposite direction (from the EV battery to the utility grid). The objective of this simulation is to determine if the converter can provide the specified discharge power while maintaining control of the DC-link voltage and complying with the battery-current limits. This assessment will enable the evaluation of whether similar control performances can be achieved in both power transfer directions. 3) G2V to V2G Mode Transition: A transition of control from charging to discharging is initiated while the system is operating. The power reference is decreased until it reaches zero, and then increased again in the opposite direction following a predetermined transition profile. The evaluation of this scenario will assess the interaction between the primary converter and secondary converter as well as the transient response of the power, voltage and current. 4) V2G-to-G2V Mode Transition: In addition to investigating the transition from G2V to V2G, we have also examined the opposite transition (from V2G to G2V). To do so, we changed the operating command from discharging to charging. We included this case in our study since both transitions may have varying transient characteristics due to the differences in converter operating conditions, battery voltage levels, and control loops interaction. 5) Varying Magnetic Coupling: To simulate the effects of variations in coil alignment and/or the state of the magnetic-link, the coupling coefficient will be adjusted from 0.15 to 0.35. The performance of the controller will be assessed during steady-state power transfer and when there are changes in power demand. Of special concern are the regulation of transferred power, the characteristics of resonant current, and whether the system can operate safely within electrical limits. 6) Variations in Electrical Load and Battery Operating Voltages: Variations in electrical load resistance will be introduced at ± 20 percent. Operating voltage of the battery will be varied from 250 volts to 350 volts. These variations will allow us to assess how sensitive our controller is to variations in the electric load and battery operating conditions. We can also record how these variations affect the ability of the system to maintain power tracking, regulate voltage, and respond to transients. 7) Robustness under more difficult operation conditions is investigated by applying both disturbances at the same time. An example would be when a reduction in magnetic coupling occurs simultaneously with a load change during a commanded G2V/V2G transition. This scenario is especially interesting because it provides an evaluation of the controller under interacting uncertainties as opposed to individual disturbances. 8) Reference-Power Tracking: Both step and ramp changes in the commanded transfer power are applied in both operating directions. The response of the system to these changes will be evaluated for its ability to track reference-power, for overshoot, settling time and the ability of the controller to continue operating in a stable manner after changes to the requested power level. Together, these three scenarios form a framework that can be used to evaluate

if using a fuzzy adaptive dual sided coordinating system will improve overall system performance within the specified operational parameters.

Comparative evaluation measures a number of performance metrics that relate to power control, rapid reaction to changes in load conditions, and how efficiently energy is converted. Transferred Power Tracking Error: This metric is used to evaluate how well each controller can adjust to new power settings, both during periods when the system is operating at a constant level (steady-state) and when the system is changing states (transient). It measures the difference between the power commanded by the operator and the power that was actually transferred to the load. The time it takes for a controlled output, such as power or voltage, to reach its final steady-state value after being disturbed (or after a new reference was set) is referred to as the "Settling Time". Settling Time gives us an idea of how well our controller responds dynamically to changes. Transient Overshoot: Maxima deviations in the transferred power, DC-link voltage and relevant converter current following changes in operating mode and external disturbances can be recorded. Reduced overshoot may imply better transient damping, so long as the reduction has not been made solely by reducing the rate at which the commanded reference trajectory is changed. DC-link voltage control: During changes in energy transfer direction and during times when the system is operating under uncertainty, monitoring of both the grid-side and the vehicle-side DC-link voltages will be used to determine how well the controllers are maintaining the intermediate energy transfer process at a stable level. Power ripple and peak current: Power transferred by the system and peak currents at each resonant frequency were evaluated to determine the effect of the converter's modulation scheme and its control coordination. If there is too much power ripple or too large of a peak current, it can lead to increased semiconductor losses, increased thermal stresses, and larger component rating requirements. Power-Transfer Efficiency: To determine end-to-end efficiency we will evaluate the relationship between the amount of electrical power received by the receiving terminal compared with how much electrical power was generated by the sending terminal. The efficiency evaluation for G2V operation will be based on the electrical power transferred from the grid-side input to the battery-side output. The efficiency evaluation for V2G operation will be based on the electrical power transferred from the battery-side output to the grid-side input. Both evaluations will use identical boundary conditions. The quality of G2V/V2G reversal is assessed through several factors including, the length of the transition period; the amount by which the voltage and current deviate from their nominal values during the transition; how much the power oscillates during the transition; and how quickly the system can return to steady-state operation after transitioning into a different power transfer direction. Robustness to Variability: Controller performance was assessed across the defined range of coupling and loading. Assessment of robustness included evaluation of the variability in performance metrics, as well as the ability of the system to maintain electrical operations within acceptable limits. These indicators will give you a second set of measurements for how well your controller works. They will also let you see the different types of compromise that occur when you want a fast response, stable regulation, low converter strain, and efficient power transmission.

The simulation process starts by validating the power-circuit model at normal operating levels. The resonant-network parameters, converter switching, DC-link control, and battery-interface operations will be reviewed to verify that the system can support stable power flow in both directions (forward/reverse). The next step after circuit validation is to implement and tune a traditional proportional-integral (PI) controller for the purpose of establishing a reference level of system performance. After establishing the reference level, we will evaluate the performance of a fixed gain dual side controller, which has been designed to operate with the exact same system parameters and operating conditions as the traditional PI controller. Lastly, we will introduce our proposed fuzzy-adaptive controller and compare its performance to both of the previously tested controllers under identical operating conditions. The electrical waveforms that correspond to each of the operating conditions and performance parameters have been measured. The parameters include the power transferred, battery voltage and current, DC-link voltage, resonant currents, converter switching commands and adaptive controller gains. I need to analyze the data to determine how well each method performs relative to the reference method (and other methods) in terms of its ability to track a steady state value, how quickly it responds to changes in the system (i.e., transient response), how well it controls power flow reversal, and how efficiently it operates. Percent improvement will be determined using only the results from the respective simulations and will be referenced to the controller and operating condition used in those simulations. Additional sensitivity analyses are carried out in order to analyze the impact of changing fuzzy membership function parameters, the use of adaptive gains, and transition-reference parameters on performance. When possible, the same simulation is re-run with varying disturbance levels and initial operating conditions to verify if the controller response is consistently produced. In addition to being evaluated based on how much a particular set of parameters affects the resulting waveform characteristics and other performance indices, the numerical convergence is assessed with respect to the impact that the selection of the solver settings and the time step for the simulation will have on these same characteristics and indices. This assessment is necessary since the distortion of switching transient behaviors due to an inadequate degree of temporal resolution can result in incorrect determinations regarding either the amount of current stress experienced by the converter or the level of efficiency at which the converter operates. The simulation methodology provides a repeatable way of assessing the proposed control scheme against existing strategies. This will allow us to assess whether fuzzy adaptive dual side coordination results in improved power tracking, mode transitions and rejection of disturbances while not creating excessive loss of efficiency or stress on the converter.

The proposed simulation framework allows researchers to study the dynamic responses of LCC-S compensated bidirectional wireless power transfer systems in a controlled environment. However, there are some limitations that need to be considered when reviewing the data from the simulations. The performance of a system is accurately predicted based upon the accuracy of the converter, magnetic-coupling, battery and loss model representations. The simplified models are likely to be unable to represent the full extent of the effects of electromagnetic interference (EMI), temperature-dependent component behavior, nonlinearities in magnetic materials, parasitic elements within switching devices, and the long term deterioration of components. Similarly, ideal measurement and communications environments can result in better control response performance than what is possible with real hardware. Therefore, communications delay, sensor noise, computation time, and the dead-time of converters must be included in future robustness studies. The fuzzy-adaptive controller has additional tuning requirements for membership function, rule base design, scale factor, and gain constraint. In addition to considering the advantages of the fuzzy-adaptive controller when determining whether to use it or not, one must consider if the benefits outweigh the disadvantages that come along with the implementation requirements as well as the computational resource requirements for real time operations. In conclusion, the Matlab/Simulink investigation will demonstrate that the suggested control system is both feasible and capable of producing similar or better results than other types of systems. It is also advised that prototype testing and hardware-in-the-loop (HIL) verification be completed after this first step in order to confirm how the controller works in real-world environments with varying levels of switching, sensor readings, data communication, and temperature. Overall, the methodology establishes a systematic framework to assess the proposed fuzzy-adaptive dual-side controller and identify its possible contributions to establishing stable and effective G2V/V2G operations in environments with coupling and varying loads.

Figure 4 compares the intended steady-state responses of conventional PI, fixed-gain dual-side PI, and fuzzy-adaptive dual-side PI control under nominal G2V and V2G operation (3.3 kW, 85 kHz, $k = 0.25$). The comparison considers transferred-power tracking, DC-link voltage regulation, resonant current, and battery current. In G2V mode, the grid supplies the battery; in V2G mode, the power reference and battery-current direction reverse. Coordinated modulation and adaptive PI gains are intended to maintain stable regulation in both modes.

Power-tracking accuracy must be considered together with current ripple and electrical stress, since small average power error does not guarantee efficient operation. Figure 4 is illustrative rather than simulation-derived; any differences in steady-state error, ripple, or regulation between controllers require verification from actual MATLAB/Simulink waveforms.

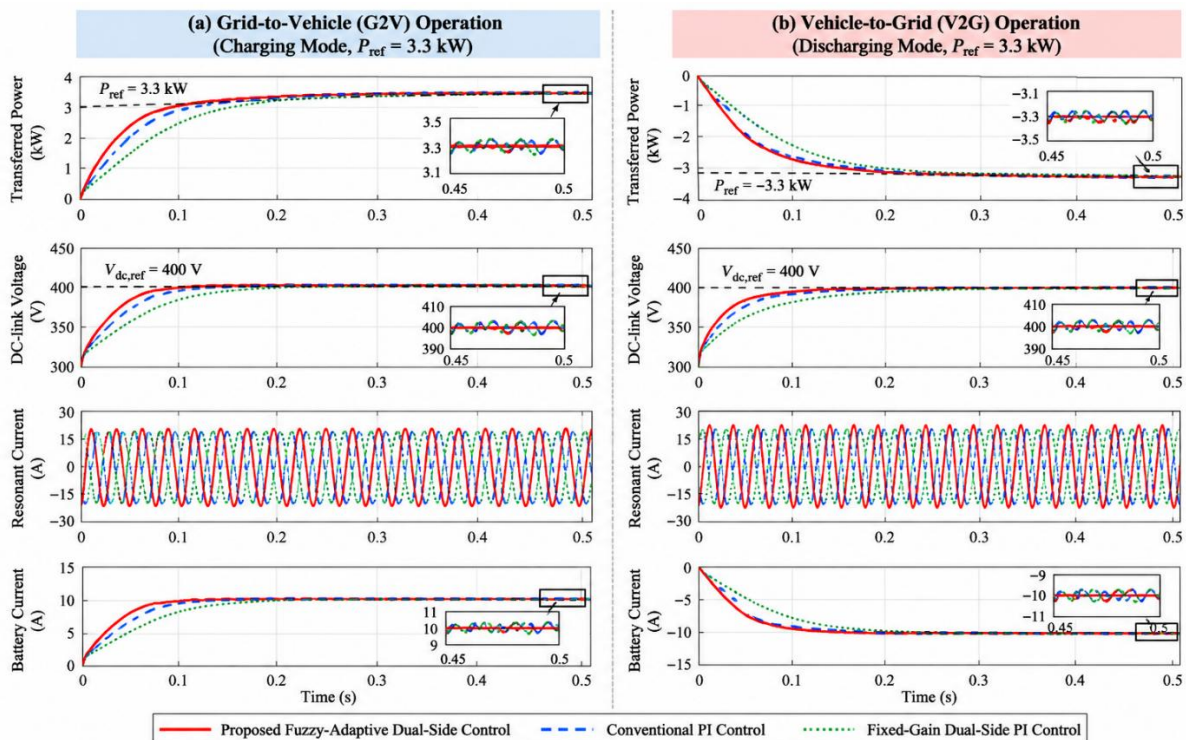


Fig. 4: Comparative steady-state performance of conventional PI, fixed-gain dual-side PI, and proposed fuzzy-adaptive dual-side control under (a) grid-to-vehicle (G2V) and (b) vehicle-to-grid (V2G) operating modes, showing transferred power, DC-link voltage, resonant current, and battery current at a nominal power of 3.3 kW and coupling coefficient of 0.25.

Figure 5 illustrates the intended response of the three controllers during G2V-to-V2G and V2G-to-G2V power reversals at nominal coupling ($k = 0.25$). The supervisory manager ramps the power reference through zero to coordinate both converters and avoid abrupt modulation changes. The fuzzy-adaptive controller adjusts PI gains according to tracking error and its rate of change, whereas the comparison controllers use fixed gains.

Performance should be assessed using reference-tracking error, transition settling time, peak overshoot, maximum DC-link voltage deviation, resonant-current stress, and battery-current excursions. Faster reversal is beneficial only if voltage and current remain within protection limits. The responses in Fig. 5 are conceptual; quantitative advantages must be measured from simulation data. The transition durations shown must also be reconciled with the 3.3 kW/s reference ramp specified in Table I.

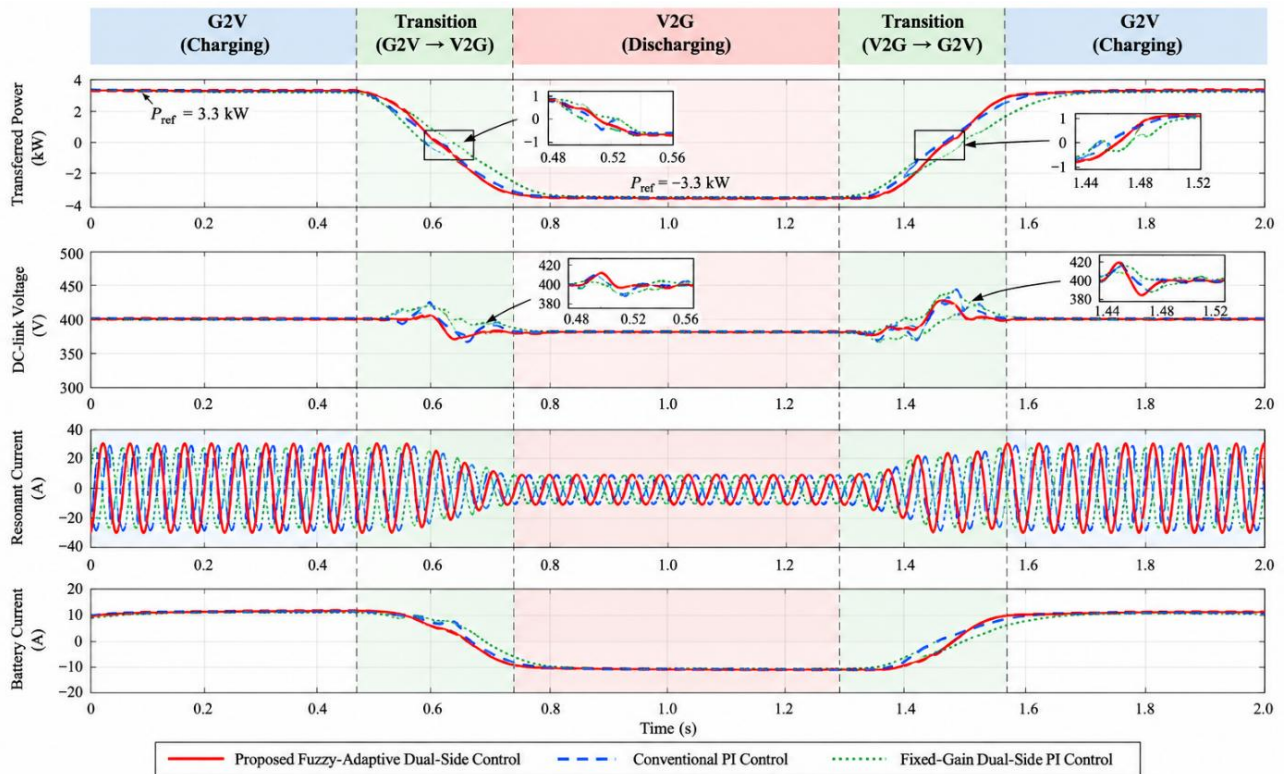


Fig. 5: Comparative dynamic performance of conventional PI, fixed-gain dual-side PI, and proposed fuzzy-adaptive dual-side control during bidirectional power-flow reversal, illustrating transferred power, DC-link voltage, resonant current, and battery current. The responses depict G2V-to-V2G (0.5–0.7 s) and V2G-to-G2V (1.4–1.6 s) transitions for a nominal transferred power of 3.3 kW, switching frequency of 85 kHz, and coupling coefficient of 0.25.

Figure 6 illustrates coupling disturbances from the nominal $k = 0.25$ to $k = 0.15$ and $k = 0.35$. Since mutual inductance depends on coupling, these changes alter the LCC-S network operating point and may cause transient transferred-power, DC-link voltage, and resonant-current deviations. Reduced coupling may require increased excitation or circulating current to sustain 3.3 kW; increased coupling may produce a transient power rise unless converter modulation is adjusted.

The three control strategies are compared under identical coupling profiles using maximum power deviation, recovery time, voltage excursion, steady-state error, and peak resonant current. The fuzzy-adaptive controller is designed to adjust gains as the operating point changes, while fixed-gain dual-side control isolates the benefit of coordination alone. If current or voltage limits prevent rated-power transfer at $k = 0.15$, supervisory derating is required. Figure 6 is illustrative and does not establish numerical performance superiority.

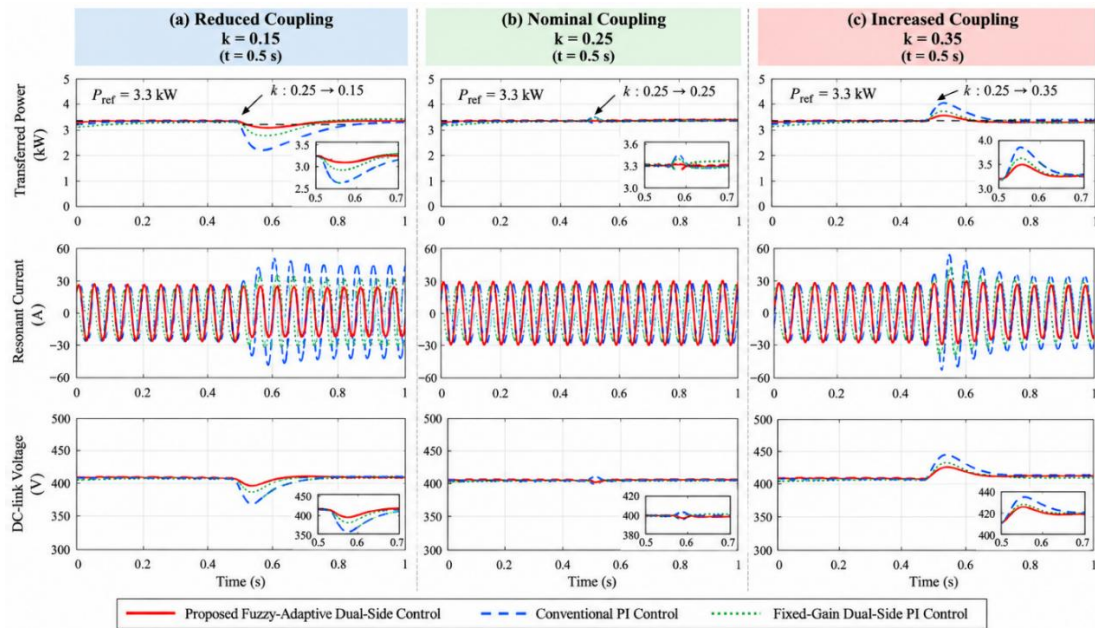


Fig. 6: Comparative transient responses of conventional PI, fixed-gain dual-side PI, and proposed fuzzy-adaptive dual-side control under magnetic coupling variations: (a) reduced coupling ($k = 0.15$), (b) nominal coupling ($k = 0.25$), and (c) increased coupling ($k = 0.35$). Transferred power, resonant current, and DC-link voltage responses are illustrated following coupling changes at $t = 0.5$ s, with a nominal transferred power of 3.3 kW and switching frequency of 85 kHz.

Figure 7 considers $\pm 20\%$ changes in equivalent load resistance and battery-voltage variations from 250 to 350 V, with nominal operation at 3.3 kW, 85 kHz, and $k = 0.25$. Load disturbances change the relationship between modulation, power, and current, while battery-voltage changes alter the required conversion ratio. The comparison examines transferred-power tracking, vehicle-side DC-link regulation, battery current, and recovery following each disturbance.

The fuzzy-adaptive controller is intended to adjust its PI gains in response to these variations, while conventional PI and fixed-gain dual-side PI retain fixed tuning. Battery-current changes should not automatically be interpreted as control errors: for constant battery power, lower battery voltage requires higher current. Accordingly, the final assessment must distinguish expected current-reference changes from overshoot and verify compliance with the ± 15 A current limit in Table I. The plotted responses are illustrative and require simulation-based validation.

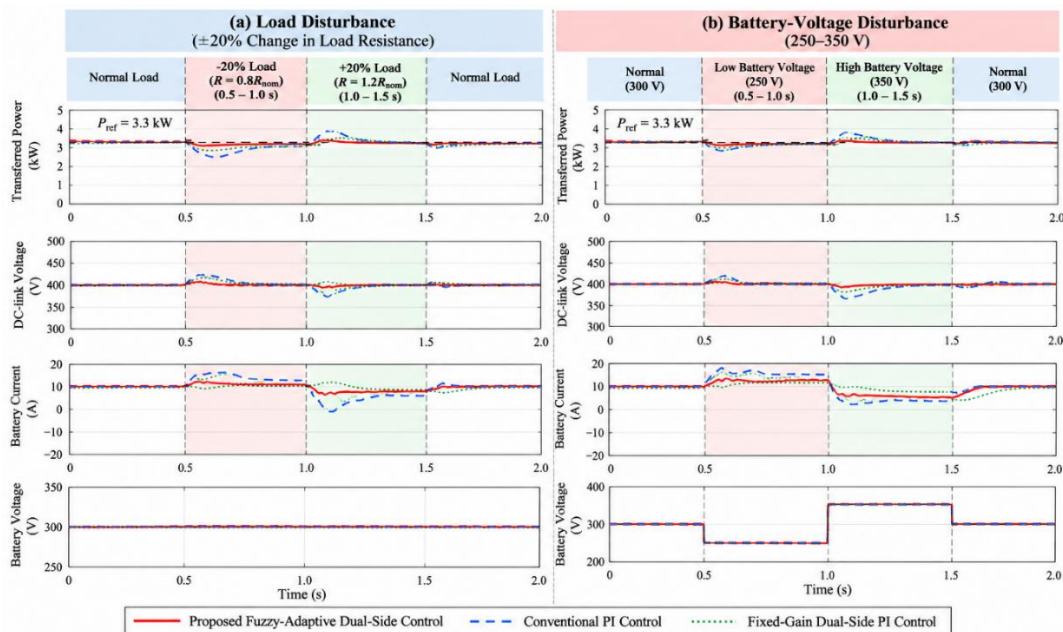


Fig. 7: Comparative transient performance of conventional PI, fixed-gain dual-side PI, and proposed fuzzy-adaptive dual-side control under (a) $\pm 20\%$ variations in equivalent load resistance and (b) battery-voltage disturbances between

250 and 350 V. The responses illustrate transferred-power tracking, DC-link voltage regulation, battery-current behavior, and battery-voltage variations at a nominal transferred power of 3.3 kW, switching frequency of 85 kHz, and coupling coefficient of 0.25.

Figure 8 outlines the intended comparison of G2V and V2G efficiency versus transferred power, magnetic coupling, and battery voltage, together with converter loss distributions. Losses arise from semiconductor conduction and switching, coil and compensation-network resistance, and other modeled converter components. Fuzzy-adaptive control does not eliminate these losses directly; any efficiency benefit would result from changes in converter modulation, circulating current, and transient behavior. Conversely, aggressive regulation can increase current stress and switching losses.

Efficiency must be calculated using consistent sending- and receiving-terminal power boundaries for all controllers, with separate G2V and V2G measurements. Loss totals must reconcile with the reported efficiency, and transient energy dissipation should be evaluated alongside steady-state operation. Figure 8 contains illustrative curves and loss values, not verified numerical results; claims of efficiency improvement must await simulation-based power and loss measurements.

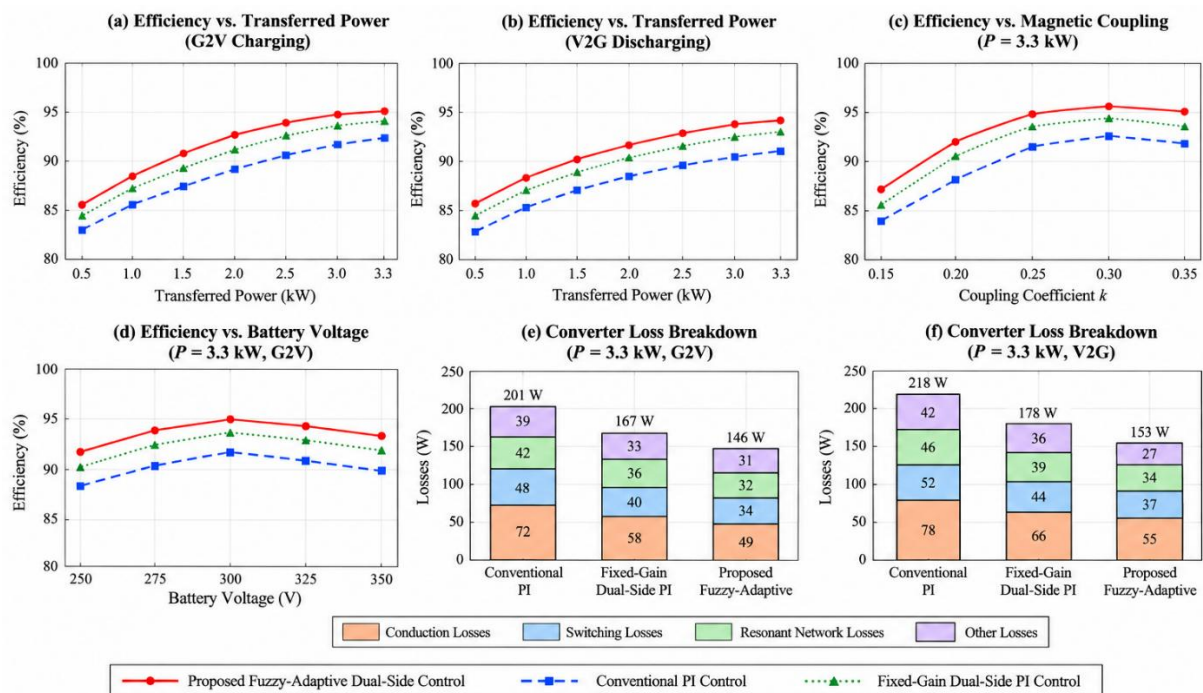


Fig. 8: Comparative energy-transfer efficiency and converter loss characteristics of conventional PI, fixed-gain dual-side PI, and proposed fuzzy-adaptive dual-side control: (a) efficiency versus transferred power during G2V operation, (b) efficiency versus transferred power during V2G operation, (c) efficiency versus magnetic coupling coefficient, (d) efficiency versus battery voltage, (e) converter loss distribution during G2V operation, and (f) converter loss distribution during V2G operation. Losses include semiconductor conduction, switching, resonant-network, and other converter losses under nominal 3.3-kW operating conditions.

Figure 9 illustrates a combined-uncertainty test involving coupling changes within $k = 0.15\text{--}0.35$, battery voltages of 250–350 V, $\pm 20\%$ load variations, and a supervised G2V-to-V2G reversal. The initial nominal charging condition provides a baseline. Subsequent combined disturbances alter the resonant-network operating point, battery-current requirements, and DC-link power balance. The mode transition then ramps transferred power through zero before reverse operation is established, followed by additional disturbances in V2G mode.

The three controllers should be tested with identical disturbance schedules, reference trajectories, and protection thresholds. Performance is assessed using maximum power-tracking error, settling and recovery times, DC-link deviation, battery-current excursions, and peak resonant current. Fuzzy-adaptive gain adjustment is intended to improve regulation beyond fixed-gain dual-side coordination, but gains remain bounded and cannot overcome physical converter limits. Where necessary, supervisory power derating takes precedence over nominal-power tracking. Figure 9 is conceptual; robustness claims require actual simulation results across the operating range.

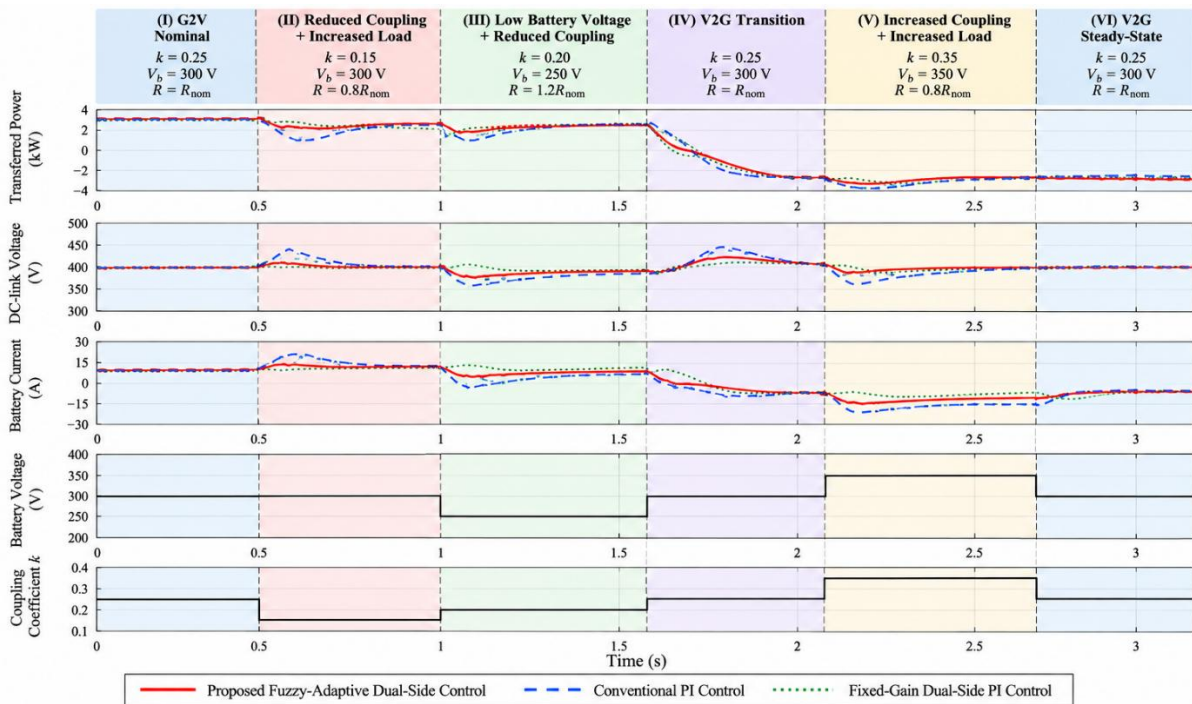


Fig. 9: Comparative robustness of conventional PI, fixed-gain dual-side PI, and proposed fuzzy-adaptive dual-side control under simultaneous magnetic coupling, battery-voltage, and load disturbances. The responses illustrate transferred-power tracking, DC-link voltage regulation, and battery-current behavior under coupling coefficient variations ($k = 0.15\text{--}0.35$), battery-voltage changes (250–350 V), and load resistance variations ($\pm 20\%$), including a G2V-to-V2G power-flow reversal between approximately 1.6 and 2.1 s, at a nominal transferred power of 3.3 kW and switching frequency of 85 kHz.

VI. Practical Implementation Considerations, Limitations, and Experimental Validation

The implementation in practice of the dual-sided fuzzy-adaptive control strategy proposed is based on a coordinated effort from both sides of the power conversion system (grid-side and vehicle-side), and it depends on a reliable set of sensors, digital controls, and communication channels. Even though the MATLAB/Simulink environment has provided a base to evaluate the performance of this control architecture, the practical use of such a system creates several additional constraints related to the switching-device properties, available computational power, accuracy of measurements, and timing requirements for real-time synchronization. The control of the proposed 3.3-kW, 85-kHz LCC-S compensated system's grid-side and vehicle-side converters can use either digital signal processor (DSP), field programmable gate array (FPGA), or another appropriate embedded controller. All of these types of controller platforms must run the regulation algorithms, fuzzy inference processes, and switching-signal generation in each of the available control intervals. The selection of the controller platform should take into account how fast the system needs to be sampled, the amount of computing power needed, and how accurately the system needs to synchronize. The fuzzy adaptive controller needs real time measurement of transferred power, DC link voltage, battery current, and resonant network variables. Those signals need to be properly filtered and scaled prior to being processed by the control algorithms. Measurement noise and signal processing delays may affect the tracking error calculation and its rate of change; consequently, the adaptive PI gains could exhibit unwanted oscillations. Therefore, a practical implementation would need to include adequate filtering, bounded gain adaptation, and anti-windup features. The second aspect to consider when using a two-converter system for EV charging/discharging is the coordination of the two converter-control sub-systems. Both the grid-side and the vehicle-side control systems must be designed to have clear regulatory goals to prevent competing control actions. One such goal could be that one sub-system would primarily regulate power transferred to the grid, while the other would maintain appropriate DC-link/battery-side conditions. Communication/synchronization mechanisms must exist so as to allow coordination of power reference signals, operating modes commands, and modulation of the converter as it switches from G2V (grid to vehicle) to V2G (vehicle to grid) operations. The switchable dead time, gate driver propagation delay, semiconductor voltage drops, and non-ideal switching characteristics must all be included in the development of the system. Each of these can impact how well the phase shift command corresponds to the transferred power, especially when operating close to zero power. As a result, it is possible that the control parameters and modulation limits developed from simulations will need to be refined during the experimental testing phase.

The effectiveness of the proposed control algorithm is dependent upon the electrical properties of the LCC-S compensation circuit and the magnetically linked coils. For practical application, it will be necessary to choose compensation components that meet both the requirements of the chosen resonant state, and do not exceed acceptable levels of stress for voltage, current and temperature. The transmitting and receiving coils are subject to variation in magnetic coupling due to changes in position, distance, and the environment's electromagnetic fields. While the current simulation assumes a range of coupling coefficient values from 0.15 to 0.35, the actual operating range for a given physical prototype will depend upon the coil's geometry, its shield configuration, the use of magnetic materials, and how it is mechanically configured. Component tolerances and temperature-dependent variations may also cause the actual resonant condition to be different than the designed resonant condition. This can result in increased circulating currents, changes in converter voltage gains, and decreased efficiency of power transfer. Although the adaptive controller that is being developed can compensate for most of the regulation errors caused by these variations, it will not be able to eliminate the inherent physical limitations of the resonant network. A critical aspect is that when operating with weak magnetic coupling, special care must be taken to ensure that the rated transferred power can still be maintained. This can be achieved by increasing either the converter excitation or resonant current. However, there is a risk that this will cause the maximum rated parameters of the coils, compensation capacitors, and semiconductor devices to be exceeded. Therefore, a practical control system needs to include both power derating and current limiting features which have higher priority than tracking the power reference. The design of the system must also consider thermal management. The loss of energy through the coil, resonant components, and power converters may result in decreased efficiency and long-term reliability. To assess these factors experimentally, it is recommended that temperature measurements are taken and that suitable cooling devices are used when operating at full load for extended periods.

The fuzzy-adaptive approach proposed here will help to enhance control system response when there are changes in magnetic coupling or electrical load. But whether it will be effective in actual application will depend heavily upon how well the reliability of the measurements, communications, and protection systems is maintained. During physical implementation, communication between the controllers on each side of the grid (grid-side controller and vehicle-side controller) can have delays in transmitting information, lose data intermittently, or be out of sync. This is especially true at times when there are transition periods between G2V and V2G operation. During these times, both sides need to change how they modulate their respective converters so that they do not create too high a voltage or current excursion. The supervisor control should determine how to react to delays in communications or unavailability of communications. Depending on the seriousness of the delay/unavailability, the system can remain operating in a safe manner temporarily; decrease the commanded power; or start a controlled shut down process. The adaptive PI gains must be constrained to a predetermined range so that the system remains stable and the control is effective. While fuzzy inference is capable of adapting to the dynamics of varying operating conditions, a poor choice of rules and/or poor selection of scaling factors can result in unwanted gain variations. Therefore, the controller must include gain saturation, rate limiting, and anti-windup protection mechanisms, which can be accomplished through systematic tuning and stability analysis. The electrical protection system will function independently from the adaptive control algorithm. Regardless of what level of output power is requested by the adaptive control algorithm, any condition (i.e., overcurrent, overvoltage, high temperature, or excessive resonant-current) that requires the protection system to take corrective action shall cause the protection system to take such action. Additionally, battery management parameters, such as maximum allowable charge and discharge rates, will be maintained during both G2V and V2G operations. The fuzzy adaptive wireless power controller will need to be connected to the grid interface protection and control functions, not as a substitute for those functions, because the bidirectional interface must meet all relevant requirements for synchronization, power quality, and safety related to disconnecting from the grid.

While MATLAB/Simulink has many advantages when analyzing complex power-electronics based systems, the results from simulations depend heavily on how well the model accurately represents the system being simulated. This study is designed to examine the effects of several types of variation (e.g., variation of coupling, battery voltage and load) on controller response. However, these are only some of the variables that may affect wireless electric vehicle charging systems in practice. The most basic of the equivalent circuit models for a magnetically coupled system does not adequately represent the effects of misaligned coils, saturation of the magnetic core, loss due to eddy currents, and the effect of frequency on resistance. Additionally, many of the equivalent circuits used to model batteries do not account for all aspects of electrochemistry and temperature in relation to state-of-charge, temperature, and degradation of the battery over time. The simulation may also underestimate the impact of parasitic elements in the switch, electromagnetic interference, sensor errors, and nonlinear characteristics of the converter. All of these factors will have an effect on the resonant current, loss associated with switching, control stability, and the precision of the estimated efficiency. Another limitation relates to the amount of computing power required to implement the proposed fuzzy-adaptive control system. While a standard digital processor may be used to implement the controller, it will have to be tested for real-time operation within the limits of the chosen sampling rate and available computing resources. Also, the added processing needed for the fuzzy inference process must be shown to lead to improved performance when compared to a simpler, fixed-gain controller. In addition to considering only a specific range of coupling and loading conditions, the investigation also evaluates whether the controller performs satisfactorily across that same range. However, performing

satisfactorily across a limited range of operating conditions does not guarantee the controller's ability to remain stable and/or robust throughout all potential operating conditions. Therefore, additional testing/analysis would be necessary to assess the controller's sensitivity to various parameter combinations, communication delays, noise associated with measuring signals, and unmodeled dynamics. The results obtained through the simulation can be considered only within the context of the simulated system and testing conditions until empirical data is produced.

An assessment of the feasibility in real world applications of the suggested control strategy will require a staged experimental verification process. This validation should begin with an evaluation of the LCC-S resonant network characteristics and converter operation at low levels of electrical power prior to moving on to the nominal 3.3-kW rating. An experimental testbed will include a two-directional grid-tied converter (active bridge), two other active bridges (one primary, one secondary), a LCC-S compensation scheme for the magnetically coupled circuit, and a programmable interface to control the battery. In order to allow for more flexibility when developing controllers, the initial implementation of the testbed could utilize either a programmable DC power supply or a battery emulation device that simulates the varying voltage of a battery. The suggested control algorithm can be implemented through a real-time digital controller. Fuzzy inference and adaptive PI gain adjustment can be processed during the selected control intervals. Sensors that measure voltage and current can provide the necessary feedback to control power, monitor DC-link, and protect against faults. The initial stage of the experimental procedure is to obtain a stable state of G2V and V2G operation under normal coupling. Once this has been achieved, the same hardware and operational parameters used for the baseline evaluation will be applied to assess the performance of the conventional PI and fixed-gain dual-side controllers. Subsequently, the fuzzy adaptive controller will also be evaluated using the same testing conditions. The evaluations will consist of evaluating steady-state power regulation, evaluation of commanded power flow reversal, evaluation of battery voltage changes and evaluating the effect of controlling the alignment of the coils. Special consideration must be given to the transitions from G2V to V2G and vice versa (V2G to G2V). It is necessary to evaluate the ability of the proposed controller to maintain reasonable DC-link voltage deviations, resonant-current stress, and power transferred-tracking during the process of transitioning through the zero-power operating state, via experimental testing. Additional studies would look into the simultaneous effects of coupling and load disturbances on evaluating whether the controller provides consistent responses when subjected to both forms of uncertainty at once. In addition, the introduction of communication delay and/or measurement noise in a controlled way would allow us to study how robust the system is to implementation issues. The experimental data will be compared to the simulation results from MATLAB/Simulink. The comparison will use equivalent performance criteria. These criteria may include, but are not limited to, the steady state error of tracking, transient overshoot, settlement time, efficiency of power transfer and maximum converter current. If there is a difference between the simulated performance and the measured performance then that difference will be analyzed to determine if there were modeling errors or areas where the controller could be refined.

Further research may enhance the proposed fuzzy-adaptive dual-side control approach by providing an even more complete optimization of bidirectional wireless power transfer systems. For instance, the system could incorporate online estimation of both magnetic coupling and resonant network parameters so that the controller would have better knowledge about the system's operating environment. Another potential avenue would be to develop dynamic supervisory control schemes which optimize the amount of energy provided by a converter, maximize the efficiency of a converter, and limit the level of electrical stress on components of a converter. These types of schemes would allow for the adjustment of the operating condition based upon the physical connection of the converter to other devices in the system, and based upon the energy needs of the battery used to power the converter. At the same time, such supervisory schemes would enable the converter to continue operating safely. The computational cost of the fuzzy inference system should be examined. It may be possible to evaluate if similar performance can be attained through simplified rule-bases, using look-up tables for implementation purposes, and/or evaluating alternative methods of gaining-scheduling in order to see if a similar level of performance can be obtained at a reduced processing cost. The use of hardware-in-the-loop (HIL) testing provides a bridge from the world of computer simulations to that of actual hardware testing. HIL testing allows researchers to assess the performance of control algorithms, the impact of time delay on sampling, the characteristics of communication links and the effectiveness of protective logic prior to installing these components onto a high power prototype converter. Future research can additionally explore how the grid-support functions can be utilized by the battery storage system such as active-power scheduling and collaborative interaction with other distributed energy sources. This type of expansion will require further exploration into the limits of the grid interface, availability of the battery storage system and the communication between the battery storage system and external energy management systems. In general, transitioning from simulation to real-world validation is critical in demonstrating that the fuzzy-adaptive dual-side control approach being developed will provide a meaningful benefit when applied to an actual dual-sided bidirectional wireless EV charging system. With the consideration of hardware nonidealities, communication requirements, resonant-network limitations, and protective coordination; future studies may assess how well the predicted dynamic response and tolerance to uncertainty can be achieved in a practical dual-sided bidirectional wireless EV charging system.

VII. Conclusions

The proposed 3.3-kW, 85-kHz MATLAB/Simulink study considers coupling coefficients of 0.15–0.35, battery voltages of 250–350 V, and $\pm 20\%$ load variation. Its comparative evaluation is designed to distinguish the effects of dual-side coordination and fuzzy adaptation using power tracking, voltage deviation, current stress, reversal dynamics, and efficiency. The figures currently illustrate expected behavior; verified quantitative findings cannot be claimed until the simulation outputs are available.

The principal contribution is the integration of fuzzy gain scheduling with coordinated bidirectional LCC-S control and protective power-transition management, together with a consistent comparison framework against conventional PI and fixed-gain dual-side PI controllers. The approach seeks robust operation across interacting disturbances without assuming that adaptation alone guarantees efficiency or stability.

Future work should validate the controller using switching-level simulations, hardware-in-the-loop testing, and a laboratory prototype, including communication delays, component tolerances, electromagnetic compatibility, thermal limits, and battery-management constraints.

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