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Design of a Feedback-Controlled Wireless Converter for Electric Vehicle Wireless Charging Applications

Mohamed O. Badawy, PhD

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DESIGN OF A FEEDBACK-CONTROLLED WIRELESS CONVERTER FOR ELECTRIC VEHICLE WIRELESS CHARGING APPLICATIONS

Mohamed O. Badawy, PhD

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16. Abstract

Electric vehicles (EVs) have played an important role in the modern transporta-tion system in recent years. However, current generations of EVs face unsolved drawbacks such as short driving range, long charging time, and high cost due to expensive battery systems. Wireless Power Transfer (WPT) is a promising technology that is able to mitigate the drawbacks EVs are facing. This paper focuses on investigating and building a complete high-efficiency WPT system that is capable of efficiently charging electric vehicles. The goal is to design and ap-ply two different configurations of compensation networks to the WPT system. In this paper, the two compensation network configurations studied are LLC and LCC. After comparing their operational characteristics and efficiencies, the most suitable configuration is proposed. Moreover, a phase-shifted controller is applied in order to regulate the power transferred through the WPT system.

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I. INTRODUCTION

Wireless power transfer (WPT), as shown in Fig. 1, is an advanced technology which is able to solve the technical drawbacks of electric vehicles (EVs). The operation of a wireless power transfer system is similar to that of inductive power transfer (IPT) technology. Indeed, in a WPT system, power transfers through mutual inductance between the transmitting and receiving coils.[1] Additionally, WPT systems eliminate any risks related to electrical shock.

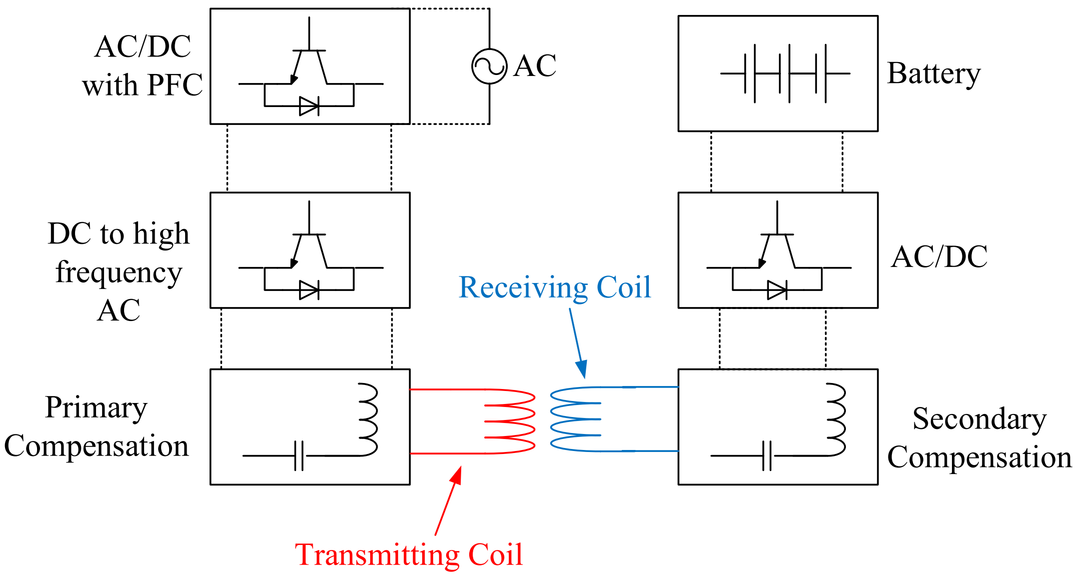


Figure 1. Wireless Power Transfer for Electric Vehicles

The complete configuration of WPT includes four main parts: input rectifier, input H-bridge inverter, resonant tank (often known as compensation network), and output rectifier, as shown in Fig. 2. This report focuses on the design of a compensation network including an LCC along with its control algorithm. Additionally, the use of an LLC network is explored in this report and a comparison analysis is conducted between the compensation networks investigated.

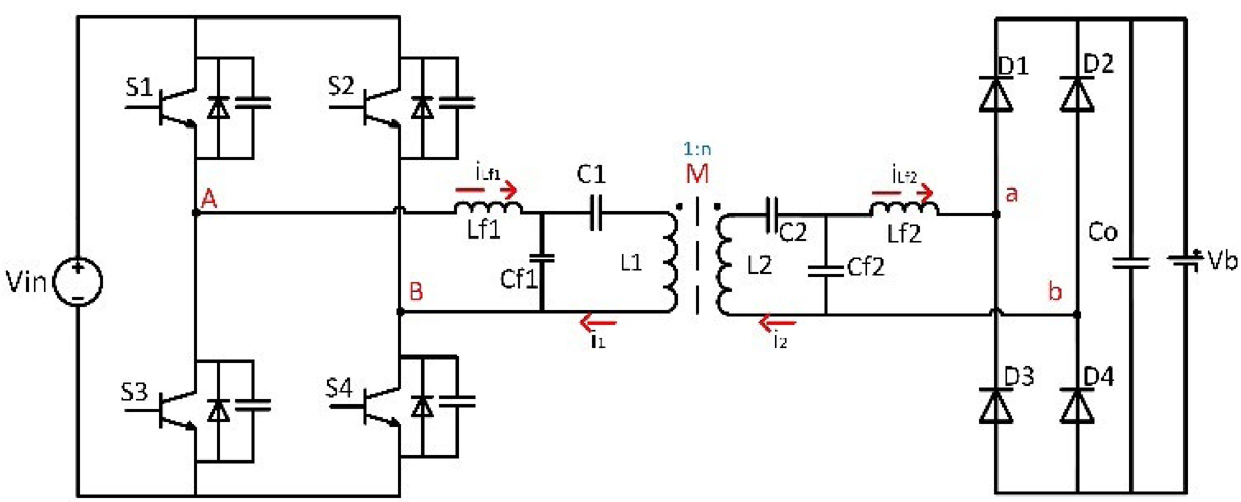


Figure 2. Dual-Sided LCC Wireless Power Converter

II. COMPENSATION NETWORK

One of the characteristics of a WPT system is that air gap variation and misalignment between two coils are unavoidable. In addition, since the air gap between transmitting and receiving coils in a WPT system is large, the coupling coefficient is small. The value of the coupling coefficient depends on the air gap, alignment, and design of transmitting and receiving coils. The most popular problem among WPT systems is that the small value of the coupling coefficient limits the power transferred through two coils. Thus, a compensation network such as LCC or LLC is required to increase the coupling coefficient. Moreover, in modern power electronics systems, achieving soft switching such as Zero Voltage Switching (ZVS) is critical in order to increase efficiency and reduce the size of the systems.[2] This report proposes two series-parallel resonant converters (SPRC) which will act as the compensation network of the WPT system.

DUAL-SIDED LCC NETWORK

The dual-sided LCC compensation network, as shown in Fig. 3, uses two capacitors and one inductor for each side. The LCC network has outstanding characteristics that are able to improve the performance of WPT systems. Particularly, LCC converter yields zero voltage switching mode; therefore, it improves the efficiency of the WPT system. Moreover, utilizing an LCC compensation network enables unity power factor for both the input side and the output rectifier.

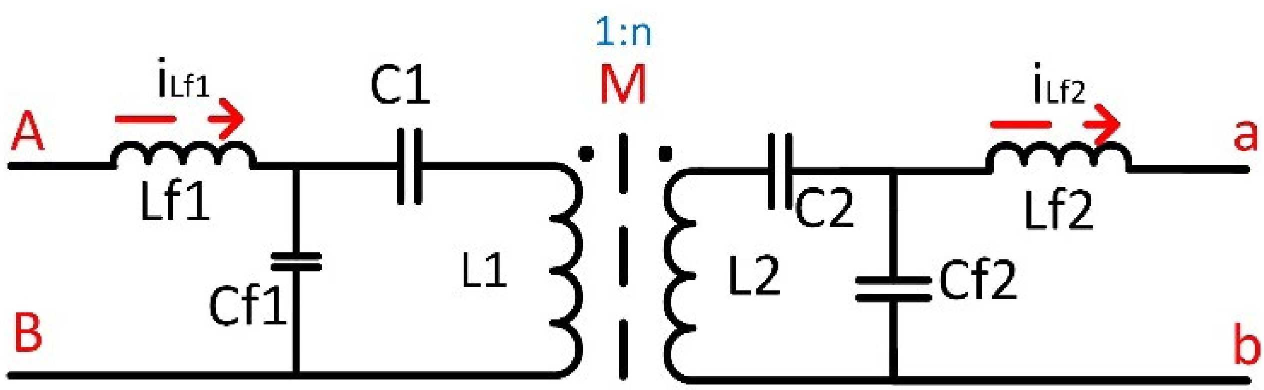


Figure 3. Dual-Sided LCC Resonant Tank

Based on the theoretical analysis, there are four important conclusions:

- If I_{Lf1} and U_{AB} are in phase ⇒ unit power factor of input side is achieved.
- If I_{Lf2} and U_{ab} are in phase ⇒ unit power factor of output side is achieved.
- The phase relation is independent of the coupling coefficient or the load variations.
- The power transferred through LCC tank depends on the coupling coefficient k and the input and output voltage of resonant tank U_{AB} , U_{ab}.

To achieve soft switching, there must be a small portion of reactive power on the primary side. Thus, the LCC network is often tuned to ensure that the phase between voltage and current is close to zero, but not completely zero. In this paper, Zero Voltage Switching is the desired mode. Since the reactive power is quite small, it does not affect the pure power factor characteristics. In particular, the phase between voltage and current is close to zero after the tuning process.[3] One method to obtain Zero Voltage Switching is to configure the system so that switches turn on with a negative current. To ensure this negative turn-on current, the turn-off current of MOSFETs has to be positive. This report proposes a tuning method that can yield conditions for ZVS regardless of coupling coefficient.

RESONANT LLC NETWORK

The LLC compensation network can control the output over wide load variation with a small change in switching frequency. Moreover, soft switching can be achieved by tuning the parameters of the inductors and the capacitor. The structure of the LLC resonant tank is depicted in Fig. 4. The configuration of the LLC resonant converter includes one capacitor and two inductors, known as an LLC structure. The first inductor L_r is called the leakage inductor, while the second L_m is the magnetizing inductor. The resonant capacitor is C_r.

The resonant frequency of the LLC resonant tank is denoted as

$$f_0 = \frac{1}{2\pi\sqrt{L_r C_r}}$$

The voltage gain function of the resonant tank is expressed as

$$M_g = \frac{L_n \times {f_n}^2}{\sqrt{\left[(L_n + 1) \times {f_n}^2 - 1\right]^2 + \left[\left({f_n}^2 - 1\right) \times f_n \times Q_e \times L_n\right]^2}}$$

where $f_n = \frac{f_{sw}}{f_0}$: normalized frequency; $L_n = \frac{L_m}{L_r}$: inductance ratio; $Q_e = \frac{\sqrt{L_r/C_r}}{R_e}$: quality factor; R_e : reflected load resistance.

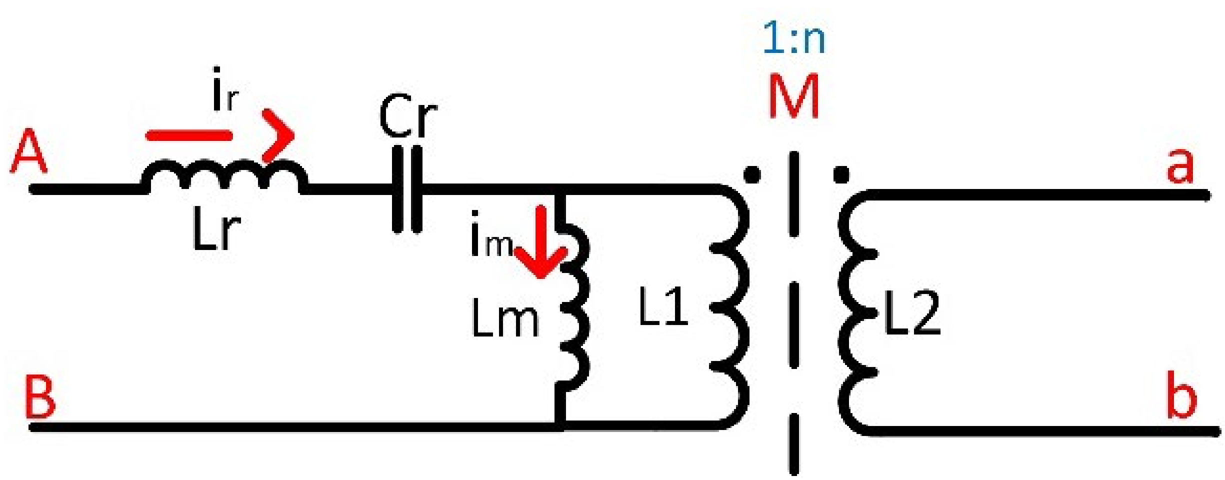
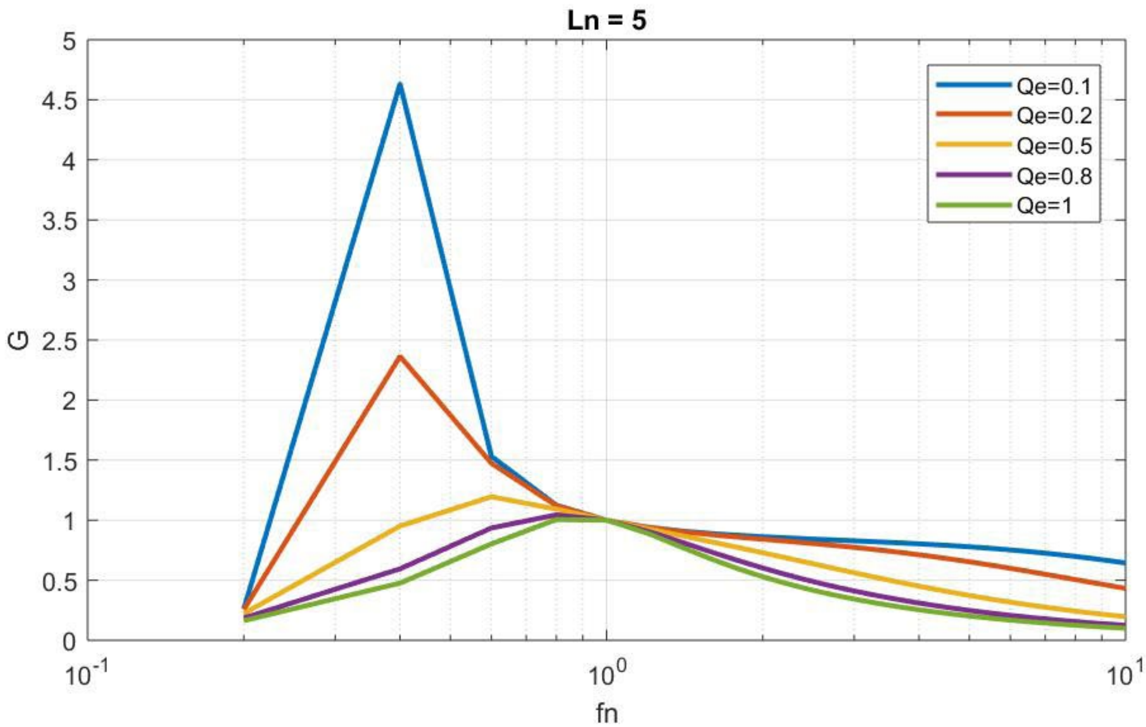


Figure 4. LLC Resonant Tank

Fig. 5 describes the curve of the voltage-gain function with the normalized switching frequency for various values of and fixed value of . In Fig. 5, lower curve represents a lighter load condition, while higher describes a heavier load operation. In addtion, each curve has a peak point such that is the maximum. To the right of the peak is the inductive operation region, and to the left of the peak is the capacitive operation region. The resonant tank is designed in order to operate in the inductive region for the entire input votage and load range and never to fall into the capacitive region. Moreover, in Fig. 5, every curve meets and goes through the point (,) = (1,1). At this point, the switching frequency is equal to the resonant frequeny and the gain of the resonant tank is unity. In other words, when , the operation of the resonant tank is independent of loading conditions. Thus, it is desirable to operate the resonant tank at . Moreover, when working at resonant frequency, LLC resonant tank yields conditions for Zero Voltage Swiching mode that increase efficiency and reduce the converter size.[4]

a)



b)

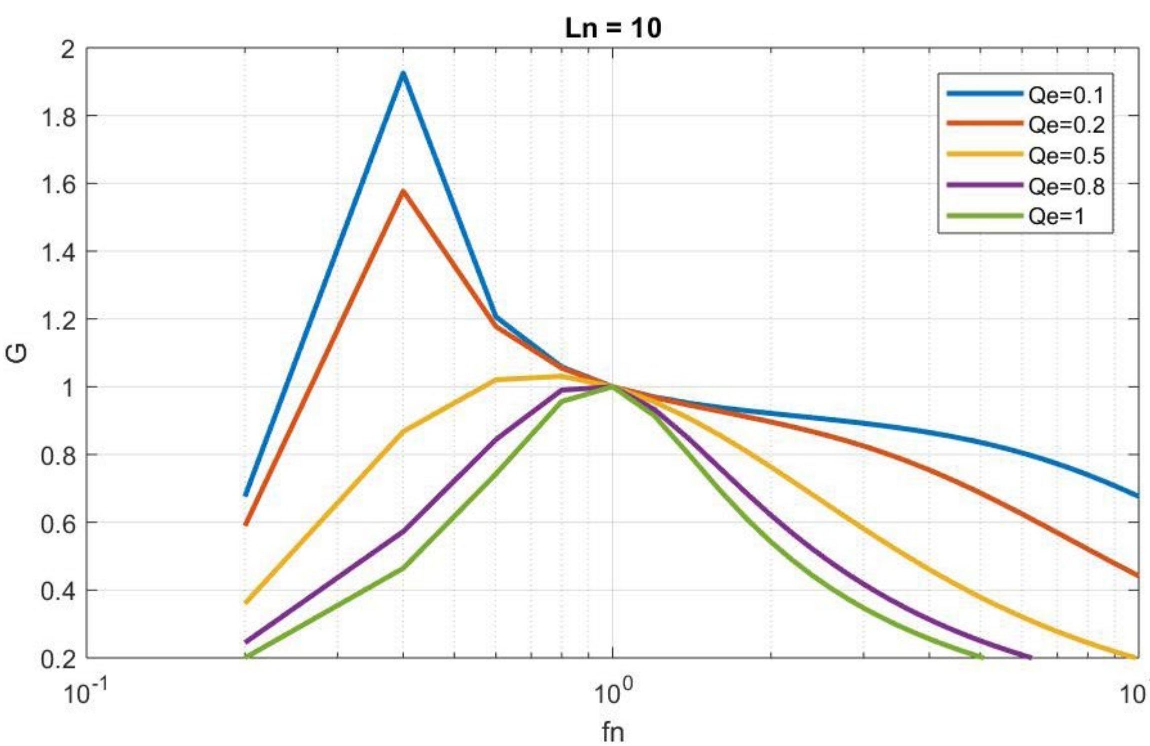


Figure 5. Plots of Voltage Gain Function for an LLC Converter

III. DESIGN OF TRANSMITTING AND RECEIVING COILS

The next step is to build a simulation model of transmitting and receiving coils in Ansys/Maxwell as shown in Fig 6. The purpose of this step is to investigate fully the operation of two coils in WPT applications. Finally, the co-simulation between Matlab/Simulink, Ansys/Simplorer, and Ansys/Maxwell will be carried out. In particular, the controller is simulated in Matlab/Simulink, the transmitting and receiving coil are simulated in Ansys/Maxwell, and the remaining parts are simulated in Ansys/Simplorer.

In this project, the Polarized Single-Sided Flux Pad topology is applied for the design of transmitting and receiving coils. Since the coils are wound like a “D shape”, this topology is also called a Double-D (DD) structure. The DD structure yields valuable characteristics which are desired for wireless charging systems with EV applications. For instance, the charge zone for a DD pad could be about twice as large compared to a conventional circular pad with similar material cost. Moreover, the DD structure is capable of improving the coupling coefficient of transmitting and receiving coils compared to traditional coil designs.

The structure of the transmitting coil and receiving coil includes two windings, which are connected magnetically in series and electrically in parallel. The coil width is made up of 20 turns of $4mm$-diameter Litz wire. The ferrite bars are implemented in order to guide and enhance the magnetic fields. In addition, an aluminum plate is used as the shielding layer and heat sink.

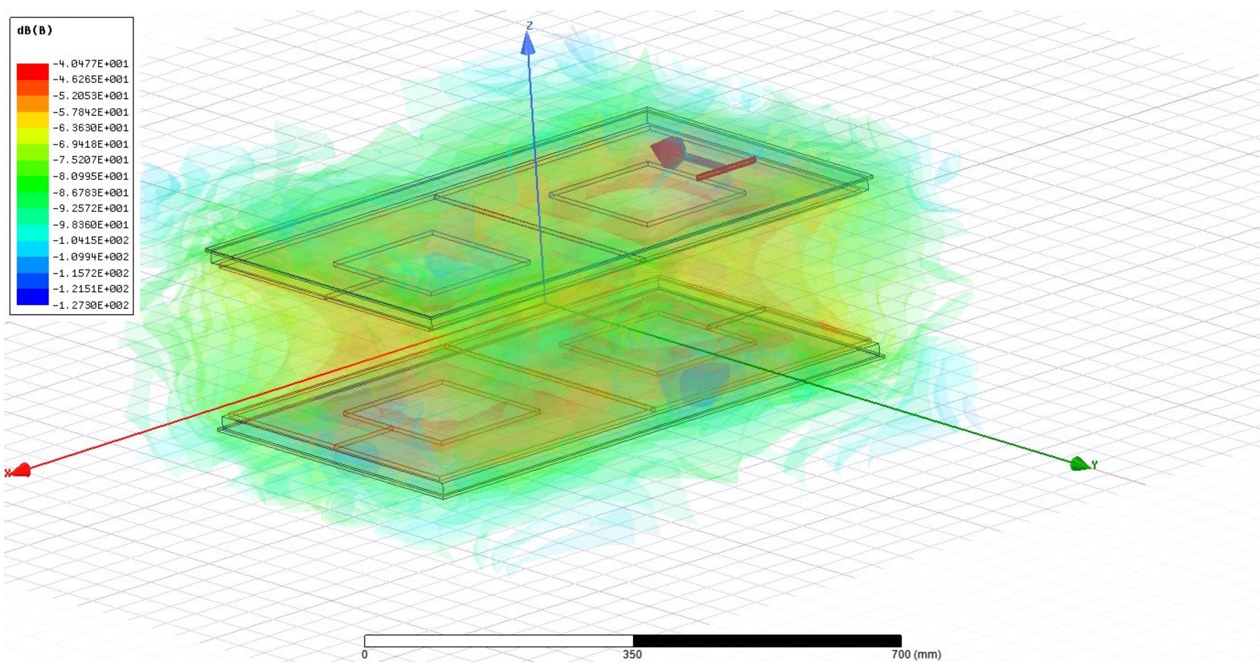


Figure 6. Single-Sided Double D Coils

IV. PHASE-SHIFTED CONTROLLER

In charging applications, there is a need to regulate the amount of energy charging the EVs. There are three popular control methods, known as primary side control, secondary side control, and dual-side control. The name of each method indicates where the control is applied. In this paper, the controller is applied at the primary side.

Primary side control could be accomplished by adjusting the switching frequency or the phase-shift between Mosfet legs. The compensation network of the WPT system is a resonant converter, thus, the switching frequency adjustment is not adequate at all loading conditions. In particular, wide switching frequency variation could lead the resonant converter to lose soft switching ability.

In this paper, the primary side control, known as phase-shifted control, is applied in order to regulate the transferred power. Fig. 7 shows the configuration of the WPT system with LCC compensation network. In the phase-shifted controller, at the first leg, MOSFETs QA and QB switch at 50% duty cycle with their PWM signals 180 degrees out of phase of each other. Similarly, at the second leg, MOSFETs QC and QD switch at 50% duty and 180 degrees out of phase. In this control method, the switching frequency is fixed and the amount of phase shift between the MOSFET legs determines the transferred power.

Figure 9 shows the configuration of the phase-shifted controller. In this controller, the J-K and RS flip-flop are implemented. The J-K flip-flop block models a negative-edge-triggered J-K flip-flop. The S-R flip-flop block models a simple set-reset flip-flop. In addition, the Monostable block generates the dead time between switches at the same leg. In this project, the dead time is 150 ns.

The remainder of this section will describe the operation of the phase-shifted controller. The PI controller (outer voltage loop) will provide the reference current I_{ref} based on the output current reference I_{o_ref} defined earlier. This reference current I_{ref} is compared to the input current of the converter (I_{dc}).

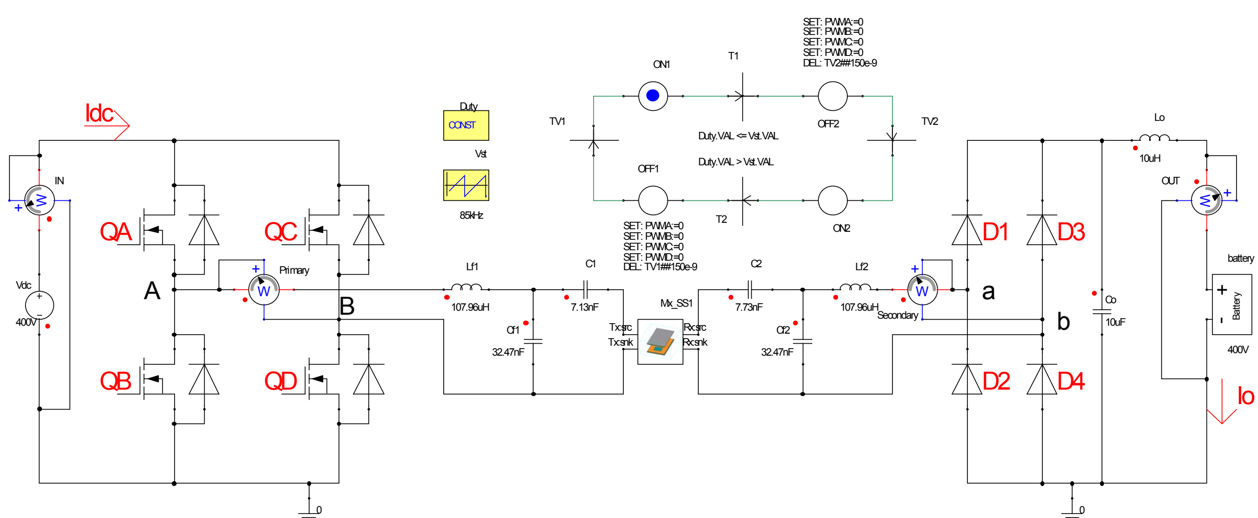


Figure 7. Wireless Power Transfer with Dual-Sided LCC Compensation Network

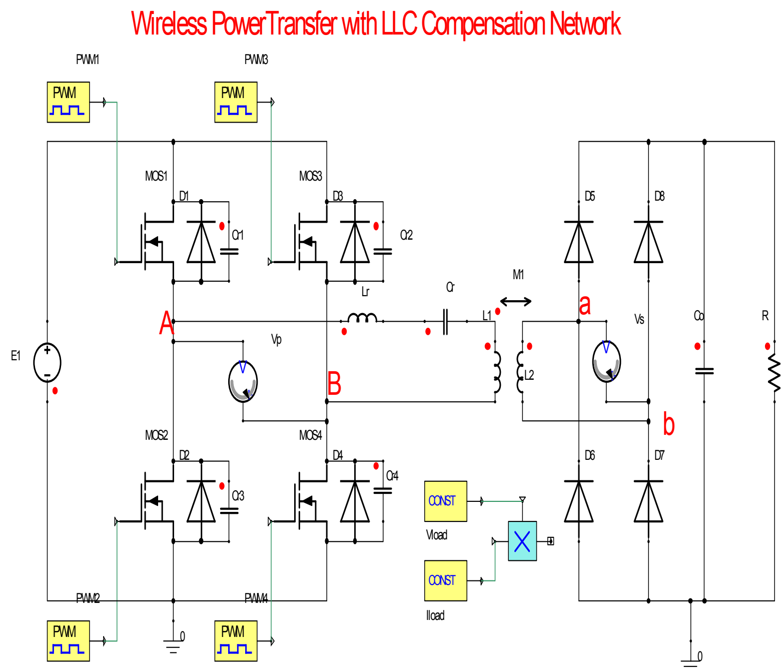


Figure 8. Wireless Power Transfer with LLC Compensation Network

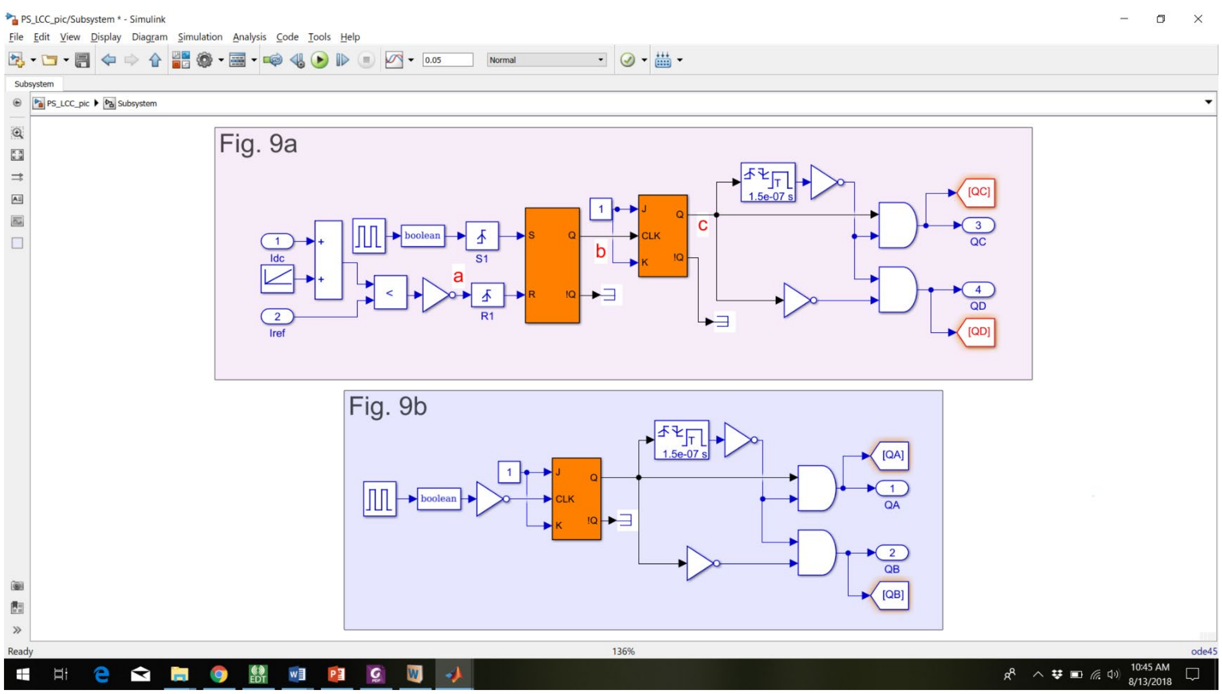


Figure 9. Phase-Shifted Control Algorithm

Figure 9b illustrates the generation of the gate drive signals of Q_A&Q_B. As is known, if gates J and K are connected to a true signal, the J-K flip-flop toggles the output Q when there is a falling-edge at the Clk gate. In Fig. 9b, the Clk gate is connected to a pulse whose frequency is $f = 170\ khz$ and the duty ratio is $D = 0.05$. This configuration gives an 85 $khz;\ D = 0.5$ pulse at the output of J-K flip-flop. This frequency is exactly the switching frequency. Then, the Monostable block excites the deadtime. Here, the deadtime is t_d

= 150 ns. In particular, the switching frequency of Q_A&Q_B is 85 khz, the duty ratio is D = 0.5, and the deadtime 150 ns. In addition, Q_A and Q_B switch 180 degrees out of phase of each other.

In Fig 9a, assume that at the beginning, Q_C = 0 and Q_D = 1. Consequently, signal c is 0. If $I_{dc} > I_{ref}$, signal a is 0, signal b is 1, and nothing changes in the circuit. This means that Q_C = 0 and Q_D = 1. However, if $I_{dc} > I_{ref}$, signal a becomes 1; therefore, there is a rising-edge signal that goes to the R gate of R-S flip-flop. Consequently, the ouput of R-S flip-flop, signal b, is reset to 0. At that time, this falling edge goes to the Clk gate of J-K flip-flop. Since both the J and K gates are connected to 1, signal c is toggled from 0 to 1 when a falling edge occurs. In other words, when $I_{dc} > I_{ref}$, the gate drive signal Q_D is reset from 1 to 0. In addition, after the deadtime t_{dead} = 150 ns, the gate drive signal Q_C is set. The analysis is the same for the case when, initially, Q_C = 1 and Q_D = 0.

Therefore, by controlling the phase between MOSFETs, it is possible to control the power transferred through the transmitting and receiving coils.

V. SIMULATION RESULTS

A simulation model of the Wireless Power Transfer system, as shown in Fig. 7 and Fig. 8, was built in Ansys/Simplorer. Simulation results agree well with the theoretical analysis. The effect of misalignment to the system was investigated by running the simulation under three different values of coupling coefficient k. Both the LCC and LLC configuration yield the desired characteristics. Nevertheless, for wireless power transfer applications, dual-sided LCC topology is more promising than LLC topology. Indeed, the LCC yields more efficiency than does the LLC topology. Also, the LCC compensation produces soft switching conditions as well as pure power factor correction. Therefore, this section focuses on the analysis of WPT with dual-sided LCC compensation network.

In addition, Fig. 10 shows the waveforms of the phase-shifted controller. According to the waveforms, there is a phase shift between QA and QD as well as QB and QC. This phase shift determines the power transferred through two coils.

Fig. 11 shows the waveform of V_{AB} & I_{AB} and V_{ab} & I_{ab}, the input and output signals of the LCC compensation network. According to the waveforms, both V_{AB} & I_{AB} and V_{ab} & I_{ab} have the unity power factor correction. Indeed, the voltage and current signals are in phase with each other. This characteristic is significant, as it maximizes the power transferred through transmitting and receiving coils.

Furthermore, as shown in Fig. 11, the LCC compensation network yields soft switching at all MOSFETs. In particular, the voltage of MOSFETs is zero when the current of MOSFETs is increasing. This means that there is no switching loss when then the MOSFETs conduct. Therefore, the total losses of a WPT system are significantly reduced by using an LCC compensation network.

Fig. 12 displays the variations in the coupling coefficient with respect to both, vertical and horizontal misalignments.

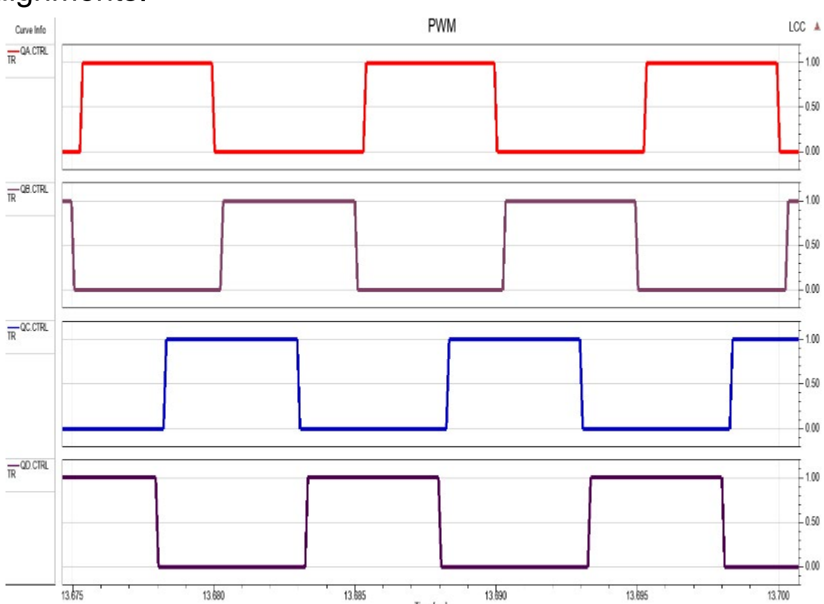
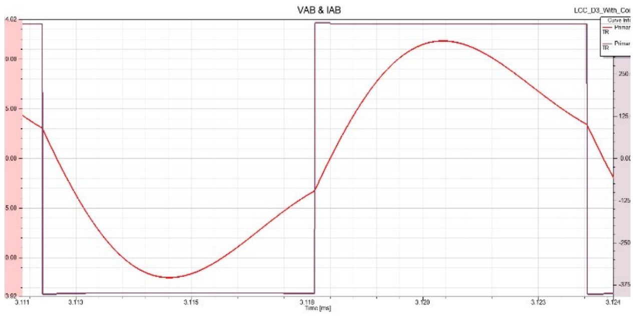
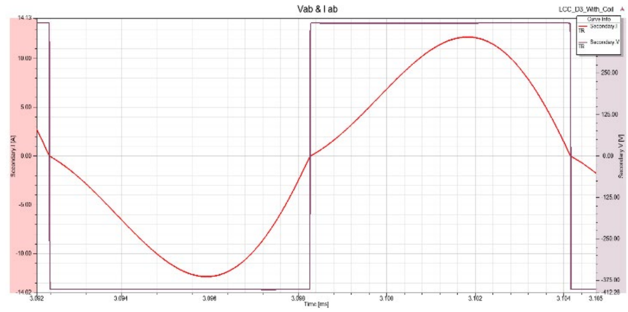


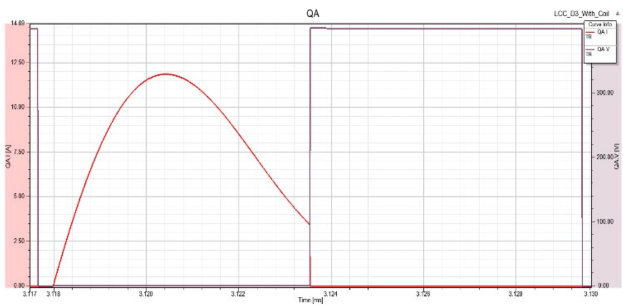
Figure 10. Phase-Shifted Control Waveform



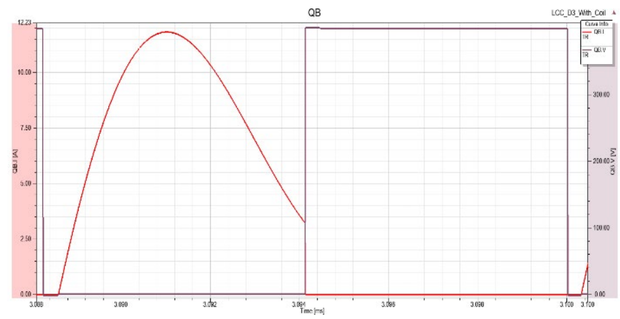
a) V_{AB}&I_{AB}



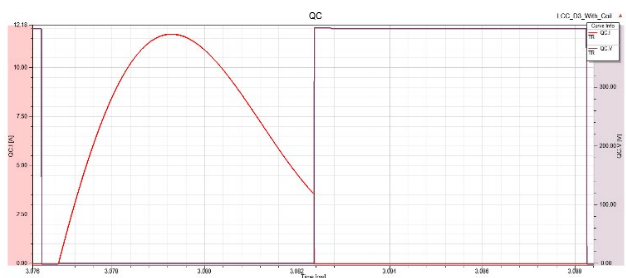
b) V_{ab}&I_{ab}



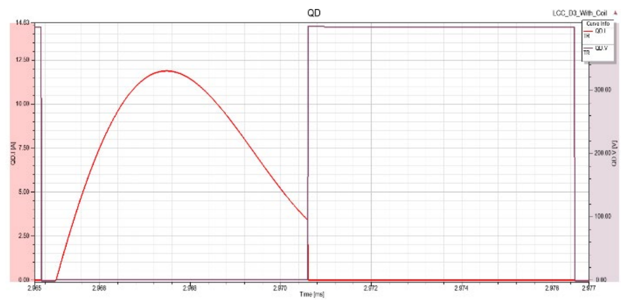
c) Voltage and Current of MOSFET QA



d) Voltage and Current of MOSFET QB



e) Voltage and Current of MOSFET QC



f) Voltage and Current of MOSFET QD

Figure 11. Current and Voltage Waveforms

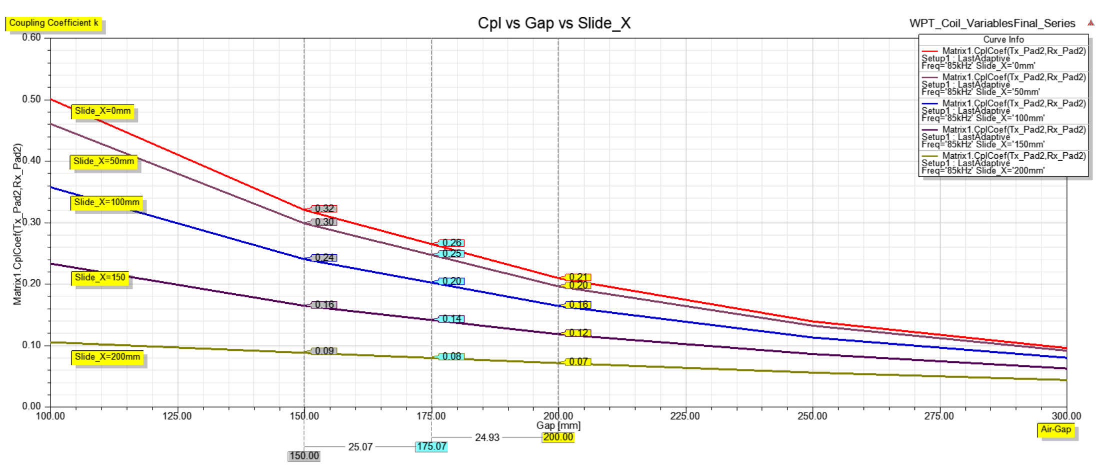


Figure 12. Coupling Coefficient – Air Gap Variation – Slide_X Misalignment

The aim of this project is to design a configuration of two coils which is able to produce a coupling coefficient k = [0.15,0.3] at the normal air gap y = 200 mm and Slide_X misalignment $Slide_X$ = 50 mm. The air gap y = 200 mm is selected since this distance is also the normal gap between an electric vehicle's floor and the ground. The preferred Slide_X between two coils is 50 mm because drivers with normal driving skills are able to park cars in that range of misalignment between the transmitting and receiving coils.

According to Fig 12, the coupling coefficient decreases when the air gap variation or Slide_X misalignment increases. Furthermore, at $air\ gap$ = 200 mm and $Slide_X$ = 50 mm, the coupling coefficient is k = 0.2.

The simulation system efficiency from a DC power source to power the electronics load is 97.48% for maximum power with coupling coefficient of 0.25.

VI. HARDWARE IMPLEMENTATION

According to the simulation results, it is concluded that for wireless power transfer for EV applications, the double-sided LCC converter is more promising than LLC. Therefore, in this project, a hardware prototype of a wireless power transfer system using Double-Sided LCC converter has been built.

The prototype design of 3.3 kw wireless charging system is designed using Altium Designer. The DSP TMS320F28379D is used in order to implement phase-shifted controller algorithm and generate PWM signals.

The specifications are as follows: input voltage is 400 V, and 3.3 kw; 400 V power electronics loads are used to take the position of a real battery pack. The 800-strand AWG-38 Litz wire is used to make the transmitting and receiving coils. The coil dimension is 740 mm length and 430 mm in width.

To ensure isolation for this high-power application, all gate drivers, sensors, and voltage regulators are isolated from the digital signal side. A four-layer printed circuit board is used to ensure compactness of the hardware.

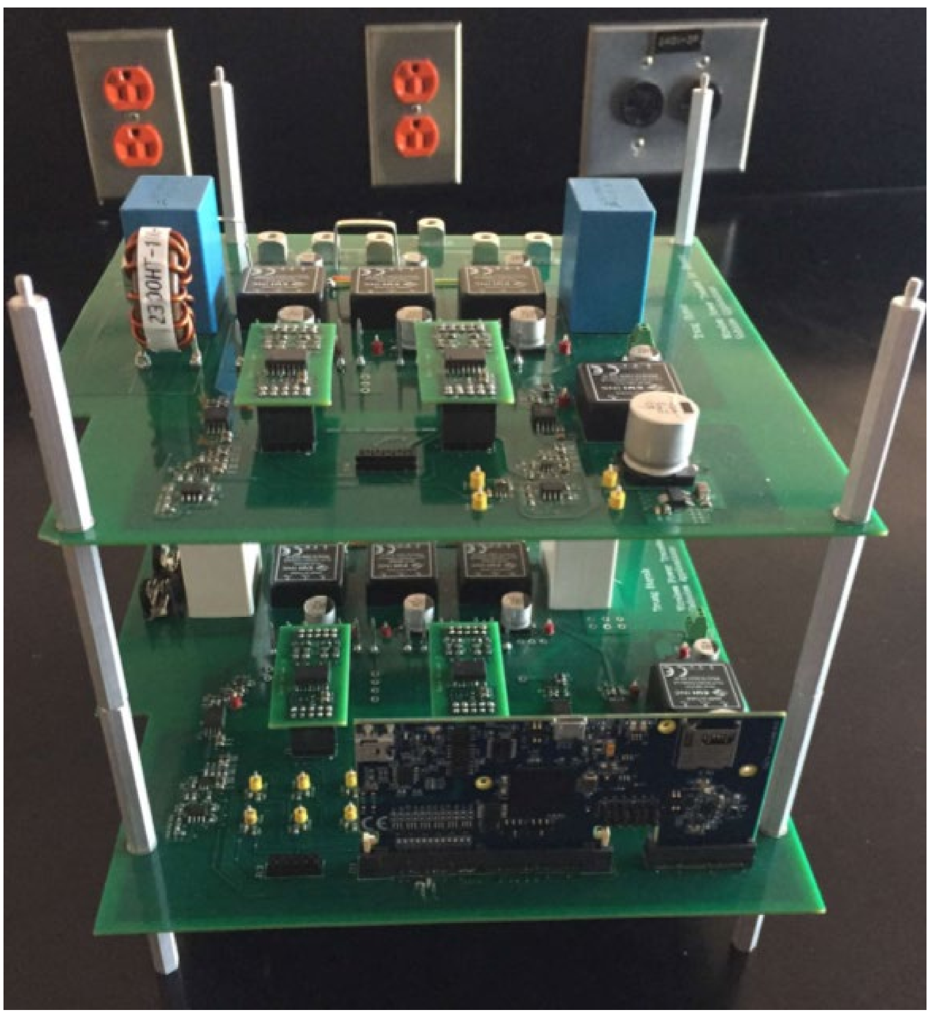


Figure 13. Developed Dual-Sided LCC Converter Prototype

VII. CONCLUSION

A dual-sided resonant LCC converter and an LLC converter are simulated and analyzed for EV wireless charging applications. The designed converter can achieve a high system efficiency due to its soft switching features. A feedback frequency control is applied on the converter to increase the system efficiency while tracking the output power. The simulation model is fully developed and analyzed using LTspice, MATLAB, and Ansys Simplorer/Maxwell. The simulation system efficiency from a DC power source to power the electronics load is 97.48% for maximum power with coupling coefficient of 0.25. A prototype is developed to prove the system's functionality and efficient performance under different operating conditions.

ABBREVIATIONS AND ACRONYMS

Please provide a list of abbreviations/acronyms and their definitions here. The template uses a table, which will be properly formatted during the publication process. Add additional rows as needed.

EV	Electric vehicle
WPT	Wireless power transfer
LLC	Inductor, inductor and capacitor
LCC	Inductor, capacitor and capacitor
L_r	Leakage inductor
C_r	Resonant capacitor
R_m	Magnetizing inductor
ZVS	Zero voltage switching
IPT	Inductive power transfer

ENDNOTES

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PEER REVIEW

San José State University, of the California State University system, and the Mineta Transportation Institute (MTI) Board of Trustees have agreed upon a peer review process required for all research published by MTI. The purpose of the review process is to ensure that the results presented are based upon a professionally acceptable research protocol.