Implementation of Identical Spiral Square Inductive Coils for Wireless EV Battery Charging Application

D. Kishan*, P. S. R. Nayak**, and B. Naresh Kumar Reddy*

Abstract: In recent years, the popularity of wireless inductive power transfer (WIPT) system for electric vehicle battery charging (EVBC) is always ever-increasing. In the WIPT inductively coupled coil structure is the heart of the system and the mutual inductance (MI) between the coupled coils is the key factor for effective power transfer. This paper presents the analysis of mutual inductance between the spiral square coils based on the cross-sectional area ratio of spiral circular and spiral square coupled coils. The analytical computed MI values are compared with FEM (ANSYS Maxwell) simulation and Experimental computed values. Finally, the designed spiral square coils are implemented in a laboratory prototype model and at the receiver side for effective electric vehicle (EV) battery charging a closed-loop PID controller is implemented for DC-DC buck converter. The effectiveness of the proposed controller has been tested by providing sudden changes in mutual coupling and change in reference value. The proposed system is suitable for both stationary and dynamic wireless EVBC.

Keywords: Inductive Power Transfer, Battery, Electric Vehicle, Mutual Inductance.

1 Introduction

The fossil fuel vehicles are causing 34% of the air pollution, which brings about expanding global warming [1]. So as to lessen this issue to some extent, it is important to confine the utilization of fossil fuels. Researchers are addressed the electrification of vehicles (EV) to overcome the pollution problem. The main advantages of electrified vehicles are operated smoothly and emission-free [2, 3]. These vehicles are operated on battery rather than fuel. Hence, electric vehicles are used heavily in marker to reduce pollution. One such significant apprehension of EV’s is the conductive battery charging (plug-in) applications [1, 2]. The plug-in or conductive battery charging requires vast establishment of charge stations, charging plug and cable can be easily damaged, stolen and sometimes user forget to plug the electric vehicle. The issues related to conductive charging can be overwhelmed by wireless charging. Wireless power can be transferred through the air. Therefore wireless electric vehicle battery charging is to simplify the consumer anxieties and speed up EV adoption [2, 3]. In wireless power transfer system, the coil associated with the source is termed as a transmitter and the coil at the load side is known as a receiver [4]. In WPT system, the power can be transferred in the form of electromagnetic energy or electrostatic energy or radiative energy. In high power rating and medium distance system, power can be transferred more likely through electromagnetic energy, which is called inductive power transfer system (IPTS). The functionality of IPTS is conventional transformer, which is based on Ampere’s and Faraday’s law.

The most important part of the IPT system is the coupled coil structure which forms the wireless link. The extensive literature has been studied and published over time. The conventional coil structures design employs E-cores and pot cores [4, 5]. However, these core structures are incompatible for electric vehicle battery charging applications. Moreover, these core designs are heavy, sensitive to horizontal
misalignments and also expensive [6, 7]. To overcome the problems associated with conventional design, various planar coil designs that are having more tolerant to misalignment are widely deployed for stationary charging of electric vehicles and these coils are into two categories as polarized pads and non-polarized pads [2, 3, 5]. The polarized pads are multiple coil pads that can couple and create the parallel, perpendicular or both the component of flux and these pads are having H-shaped ferrite bar with double side winding [6, 8]. However, these pads also generate flux out the back of the pad, therefore when an aluminum backing plate is added it generates more loss, in the form of eddy current than that usually expected for an EV charging system. To overcome the aforesaid limitations of the H-shaped coil, single-sided pads were developed. The non-polarized pads are single coil pads which can generate only perpendicular flux. The spiral circular and spiral square coils are the most commonly used since these are nonpolarized coils. These coils have the tolerance to misalignment in all directions, easier to operate. They are nondirectional, i.e., a vehicle can approach them from any direction. Hence, spiral square coils are adopted in this work.

In WIPT system the power can be transferred when the magnetic fields generated by the transmitter coil are picked up by the receiver coil, due to limits of the misalignment and vertical distance between the coils mutual inductance deficiency will occur. The varied air gap and horizontal misalignment lead to varied coupling i.e., varied mutual inductance (MI) between the coils. Thus, the electrical characteristics of the overall IPT system can be seriously changed. [7, 8]. Hence, computation of MI is the key factor. Recently few methods are reported for computing MI [9-12]. These methods require complex computations and are also less accurate due to parameter sensitivity. The Neumann’s equation-based MI computation for spiral circular coils at different misalignments is presented [10] and it is considered in this work for spiral square coils based on the ratio of areas of the spiral circular and square coils. In WIPT system to reduce the VA rating (ratio of maximum source apparent power to load nominal power) and improve the power transfer capability of the system, capacitor compensation is essential. Since last decade tremendous research work has been presented in literature [11-13]. Further, [13] and [14], have described the conventional four compensation topologies other than dual side LC [13] compensation topologies. Among all compensation techniques, series/series (S/S) compensation is simple to design and economical hence S/S compensation topology is adopted [11, 12].

The controllers involved in the WIPT system should be adaptive, comprehensive, and easy to provide stable and efficient charging power to the load, even when the coupling effect is changed. Constant and variable frequency control methods are major control techniques for inverter of the transmitter coil. In constant frequency control method, the inverter switches are forced drive at predetermined value of switching frequency, hence it does not vary with any changes in the WIPT circuit parameters [15, 16]. In this type of control method, the operating frequency is constant and system will be stable frequency point of view. In the variable frequency control method, the frequency variation is allowed within its specific limit of range to follow the resonance [17, 18]. The disadvantage associated with this method is the operating frequency will affect the load changes and parameter variations. In this work, constant frequency and constant duty cycle control method is employed for high-frequency full-bridge inverter and at the receiver side DC-DC buck converter is employed to control the battery charging voltage regulation by using feedback closed-loop PID controller.

The organization of the paper is as follows, Section 2 describes the modeling of SS resonant WIPT system and analytical modeling of the spiral square coils. Section 3 investigates the MI between the spiral square coils at different misalignment conditions. Section 4, the implementation results of the WIPT system for battery charging application and the efficiency, charging current analysis at different misalignments is clearly presented. Finally, Section 5 concluded the paper.

2 Analytical Modelling of the WIPT System

2.1 Modeling of SS Resonant WIPT System

The equivalent circuit model of the series-series resonant wireless inductive power transfer system is shown in Fig. 2. The transmitter side of the SS-RWIPT is fed by the high-frequency AC voltage (V1) from output of the full-bridge inverter. On the receiver side, a high frequency induced voltage is converted into pulsed DC voltage using diode bridge rectifier and it is filtered using a capacitor (C1). The SS compensated capacitor of the resonant WIPT system is given below.

\[ C_1 = \frac{1}{\omega_0^2 L_1}, \quad C_2 = \frac{1}{\omega_0^2 L_2} \]  

(1)

The schematic equivalent circuit of S/S compensated resonant WIPT system is shown in Fig. 1. The maximum power transfer efficiency (PTE) and inductive coupled coil impedances can be calculated by using the following equations.
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\[ Z_1 = j\omega L_1 + R_1 + \left( \frac{1}{j\omega C_1} \right) \] (2)

\[ Z_2 = j\omega L_2 + R_2 + \left( \frac{1}{j\omega C_2} \right) \] (3)

\[ I_1 = \frac{V_1(Z_2 + R_L)}{(Z_2 + R_L)(Z_1 + R_L) + (j\omega M)^2} \] (4)

\[ I_2 = \frac{V_2(Z_2 + R_L)}{(Z_2 + R_L)(Z_1 + R_L) + (j\omega M)^2} \] (5)

At the condition of resonance, the overall reactance of the coupled coils will become zero. The output and input power are as follows

\[ P_{\text{output}} = \frac{V_1(j\omega M)}{(Z_2 + R_L)(Z_1 + R_L) + (j\omega M)^2} R_L \] (6)

\[ P_{\text{input}} = \frac{V_1(Z_2 + R_L)}{(Z_2 + R_L)(Z_1 + R_L) + (j\omega M)^2} R_1 \]
\[ + \frac{V_2(j\omega M)}{(Z_2 + R_L)(Z_1 + R_L) + (j\omega M)^2} (R_L + R_2) \] (7)

\[ \eta = \left( \frac{\omega^2 M^2 R_L}{\omega^2 M^2 R_L + (R_1 + R_2)(R_L + R_2)} \right) \] (8)

2.2 Analytical Modeling of Spiral Square Coils

A modified Wheeler formula can be used for calculations of self inductance of planar spiral square inductive coils and it is presented in (9) [8].

\[ L_s = \frac{2\mu N^2 P}{\pi} \left( \ln \left( \frac{2.067}{Q} \right) + 0.17Q + 0.125Q^2 \right) \] (9)

where \( N \) = number of turns and
\[ P = 0.5(r_{out} + r_{in}) \] = mean radius of the coil,
\[ Q = \frac{(r_{out} - r_{in})}{(r_{out} + r_{in})} . \]

2.3 Misalignments of the Spiral Square Coils

This subsection provides possible alignments of the inductive couple coils. These alignments may occur in real-time applications due to the unequal surface of the transportation roads. All these alignments are used for computing mutual inductance, charging current and overall efficiency of the WIPT system.

3 Investigation of Mutual Inductance between Spiral Square Coupled Coils

3.1 Analytical Computation of MI

The misalignments of the spiral square coils, the same as spiral circular are given following sections and also the analytical calculations are carried out for the mentioned misalignments of the circular coils only. The area of the square coil with the same diameter of the spiral circular coil is \( 4/\pi \) times higher. Thus the MI between the planar spiral square coil can be calculated using (10). The computation of MI for identical spiral circular coils is adopted from [10] and also presented in the appendix.

\[ M_\theta (\text{square}) = \left( \frac{4}{\pi} \right)^2 M_\theta (\text{cir}) \] (10)

3.2 Computation of MI through FEM Modelling

A 3-D FEM modeling tool ANSYS Maxwell 14.0.0 has been used for validating the analytical computed MI between the spiral square coupled coils. The spiral square coil setups developed in the FEM simulation at different misalignments are shown in Fig. 4.

Fig. 5, depicts the magnetic field distribution between the spiral square inductively coupled coils at 100mm distance at perfect alignments condition. Fig. 5(a) provides magnetic field distribution between the spiral square coupled coils without a core. Similarly

\[ \text{Fig. } 2 \text{ Representation of a spiral square coil.} \]
Fig. 4 Spiral square coil arrangement in FEM simulation; a) Perfect alignment, b) Lateral misalignment, c) Angular misalignment, and d) Planar and angular misalignment.

Fig. 5 Magnetic field distribution between the coupled coils at 100mm vertical distance; a) Perfect alignment, b) Lateral misalignment (40mm), and c) Angular misalignment (30°).

Fig. 6 Alignments of square coupled coils in the laboratory; a) Perfect alignment, b) Lateral misalignment, c) Angular misalignment, and d) Planar and angular misalignment.

Figs. 5(b), and 5(c) show at planar and angular misalignments, respectively. It observed that the magnetic flux density is more in case of perfect alignment compared to the planar and angular misalignments.

3.3 Validation of MI through Experimentation

The experimental prototype model developed in the laboratory is shown in Fig. 7. The developed setup consists of spiral square coils, Arduino microcontroller, and MOSFET H-bridge inverter. The spiral square coils are made up of 0.1mm/1500 strands Litz wire and manually created misalignments of the spiral square inductive coils are shown in Fig. 6. The receiver coil open-circuit voltage has been measured and the MI is computed using (11).

\[
MI = \frac{V_{oc}}{\omega I_1}
\]  

(11)

3.4 Comparative Analysis of MI

The analytical computed MI are compared with FEM simulation results and experimental computed values. Fig. 8. shows the variation of mutual inductance at different alignments with different vertical distance between the inductive coupled coils and all these misalignments are created in simulation and experimentations. As, the distance between the coupled coils increases the mutual coupling decreases, which results in the reduction of MI and also as misalignment...
distance increases which also effects the MI. The MI at manually created alignments such as perfect alignment, planar misalignment (40mm), angular misalignment (30°) and planar and angular misalignments (40mm & 15°) are presented in Figs. 8(a), (b), (c), and (d), respectively.

4 Implementation Spiral Square coils for WIPT

The developed spiral square coupled coils are implemented in a laboratory prototype. The efficient charging of EV battery requires either constant voltage or constant current supply mode. In this regard, the receiver coil generates high-frequency voltage and when it is connected to the load, the current starts flowing to load. The high-frequency AC power converts into a DC power using a full bridge diode rectifier. The out of the diode bridge rectifier is pulsating DC. In order to obtain pure DC filter capacitor is used. For efficient battery charging, depending on the voltage specification of the battery, the DC-DC converter can be selected. In this work, DC-DC buck converter is chosen. The closed-loop modeling steps of the DC-DC buck converter is presented in [19]. The transfer function of the non-ideal buck converter is given by (12) [19].

\[
\frac{v_o(s)}{d_o(s)} = \frac{7879.92s + 2984414390.3}{s^2 + 658.3512s + 2995313.126.3} \tag{12}
\]

Using the open-loop transfer function derived [19], the step response and frequency response of the buck converter can be obtained. Through step response, the dynamic performance of the system can be evaluated and stability analysis can be done through frequency response. Using the Bode plot method, Gain margin (GM) and Phase margin (PM) can be determined and these two values bound the behavior of the closed-loop system [19]. The obtained PID controller gain values are \(KP=0.12\), \(KI=11.32\), and \(KD=18\) and the following case studies were performed for testing the designed controller.

Case I: Change in reference voltage at the fixed load

Case II: Change in mutual coupling at a fixed load

All the case studies have been performed for load resistance (8Ω) for the CV charging mode and the input power is supplied from a DC constant source 600W.

Case I: Change in reference voltage at the fixed load

To test the robustness of the designed controller, the battery reference voltage has been stepped down from 60V to 50V at a fixed load resistance \(R_L\) of value 8Ω. Fig. 9 shows the transient performance of experimental results. From the results, it is clear that no transient occurs due to the appropriate controller design.

Case II: Change in mutual coupling at a fixed load

To check the performance of the controller at variation of alignment between the coupled coils,
transmitter and receiver, planar misalignment of the receiver with respect to transmitter was manually created (40mm). The battery reference voltage was kept at fixed 60V. The results observed are shown in Fig. 10. The output battery charging voltage is maintained at constant 60 volts. The current and power analysis of the SSRIPT system is shown in Figs. 11(a) and 11(b), respectively. It is observed that at zero misalignments (at perfect alignment) the charging current is higher while misalignment distance increases the charging current decreases which results in higher in charging time.

The overall system efficiency (input DC to output DC) is measured at various alignments of the coupled coils and it depicted in Fig. 11(c). It is clear that as the distance between the coupled coils increases, the overall efficiency of the system decreases i.e., the losses in the system increases. However, the experimental setup developed was for proof of concept, hence the achieved efficiency is relatively low. The overall efficiency of the system further can be improved by increasing the power rating and providing proper cooling to the system.

5 Conclusion

This paper investigates the computation of mutual inductance between the spiral square coils based on the cross-sectional area ratio of spiral circular and spiral square of the coupled coils. The analytical computed MI values are compared with FEM (ANSYS Maxwell) simulation and Experimental computed values. The designed spiral square coupled coils are used for...
validating WIPT system in laboratory model. At the receiver side of the WIPT system for effective electric vehicle (EV) battery charging a closed-loop PID controller has been implemented for DC-DC buck converter. The effectiveness of the proposed controller has been tested by providing sudden changes in load, mutual coupling and change in reference value. The proposed system is suitable for both stationary and dynamic wireless charging of electric vehicles.

Appendix

Table 1 Specifications of the WIPT System.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Frequency (f)</td>
<td>31.6 kHz</td>
</tr>
<tr>
<td>Transmitter coil self inductance (Li)</td>
<td>56.46 μH</td>
</tr>
<tr>
<td>Transmitter coil internal resistance</td>
<td>24 mΩ</td>
</tr>
<tr>
<td>Receiver coil self inductance (L2)</td>
<td>56.46 μH</td>
</tr>
<tr>
<td>Receiver coil internal resistance</td>
<td>23 mΩ</td>
</tr>
<tr>
<td>DC Input voltage</td>
<td>120 V</td>
</tr>
<tr>
<td>Load resistance</td>
<td>8 Ω</td>
</tr>
<tr>
<td>Maximum input power</td>
<td>600 W</td>
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<table>
<thead>
<tr>
<th>DC-DC buck converter specifications</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance (L2)</td>
<td>5 μH</td>
</tr>
<tr>
<td>Capacitance (C_l)</td>
<td>680 μf</td>
</tr>
<tr>
<td>Internal resistance of the capacitor (r_c)</td>
<td>0.21 Ω</td>
</tr>
<tr>
<td>Internal resistance of the inductor (r_l)</td>
<td>0.56 Ω</td>
</tr>
<tr>
<td>Battery equivalent load resistance (R_b)</td>
<td>8 Ω</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>10 kHz</td>
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<tr>
<td>Compensation capacitor</td>
<td>0.3 μf</td>
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<table>
<thead>
<tr>
<th>Coil dimensions</th>
<th></th>
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<tbody>
<tr>
<td>Number of turns in transmitter</td>
<td>20</td>
</tr>
<tr>
<td>Number of turns in receiver</td>
<td>20</td>
</tr>
<tr>
<td>Inner radius of the coil</td>
<td>21 mm</td>
</tr>
<tr>
<td>Coil design type</td>
<td>Spiral square</td>
</tr>
</tbody>
</table>

References


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