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Improving Efficiency of a Wireless Power Transfer (WPT) System by Increasing Coil-Width

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Abstract: Efficiency of a wireless power transfer (WPT) system depends on the resonance components and mutual inductance between primary and secondary coils of the transformer. Therefore, design of coils of a transformer is very crucial in WPT system as primary and secondary coils of the WPT transformer are separated by a large air gap. Due to large air gap between primary and secondary coils, coupling coefficient in a WPT system is very low compared to conventional transformer. Therefore, efficiency of the system is very low. In this paper, it is discussed that efficiency of a wireless power transfer (WPT) system can be enhanced by increasing its coil-width.
Keywords: Wireless Power Transfer, Self-inductance, Mutual Inductance, Coupling Coefficient, Coil-width.

I. INTRODUCTION

Wireless power transfer (WPT) system is a two-coil system, namely primary and secondary windings demonstrated by a century ago by several famous scientists like Tesla, Hutin and Leblanc [1, 2]. Electromagnetic induction principle utilizes the magnetic coupling between transmitting and receiving coils for power transmission and in a WPT system power is transferred between the two coils through an air gap (without core). The magnetic coupling in WPT systems is very weak due to large air gap. This is one of the major drawbacks of a WPT system. To improve the magnetic coupling for delivering the required power to the load, WPT systems are always operated at high frequency. However, at high frequency, switching losses are incurred, which affect the efficiency of the system. Therefore, WPT systems are usually operated at resonant frequency. Resonant circuits are normally employed in the primary and/or secondary circuits to boost the power transfer capability, while minimizing reactive power requirement from the source.

However, in WPT system, power is transferred from source to the load over a large air gap. Therefore, the coupling coefficient of WPT transformer is very low thereby reducing the overall power transfer efficiency of the system. The efficiency of a conventional WPT system depends on the air gap between the transmitting and receiving windings. Efficiency drops rapidly as air gap distance increases. In order to achieve a reasonable level of efficiency and transfer distance, the use of the relay resonators based on the maximum efficiency principle have been considered in [3].

II. MAGNETIC RESONANT COUPLING OF A WPT SYSTEM

A low mutual inductance results in less voltage across the receiver side. The reactive voltage drop across the leakage reactance will cause a delay between the voltage and the current resulting in a low power factor. To maintain the power factor as high as possible in a WPT system, WPT system is to be operated at resonance [4, 5]. An inductance causes the current to lag 90° compared to the voltage whereas a capacitor leads the current 90°. Inductive reactance and capacitive reactance can be expressed as follows:

$$X_L = j\omega L, \qquad X_C = \frac{1}{j\omega C} \tag{1}$$

If these two reactance becomes equal, voltage and current will be in phase. To determine the value of the compensation capacitance, the inductive reactance and capacitive reactance will be equal and the following relations will be obtained:

$$\omega_0 L = \frac{1}{\omega_0 C}, \qquad L = \frac{1}{\omega_0^2 C}, \quad C = \frac{1}{\omega_0^2 L}, \quad \omega_0 = \frac{1}{\sqrt{LC}} \tag{2}$$

Capacitors are used for compensation in both the primary and secondary windings of the transformer to improve the efficiency and the power transfer capability of the WPT system [6]. The secondary compensation is used for boosting the power transfer capability of the WPT transformer and the primary compensation is used to reduce the VA ratings of the source side converter. This is called magnetic resonant coupling.

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Magnetic resonant coupling can be attained by connecting compensation capacitors in various techniques and the techniques are termed as compensation topologies. The compensation capacitances can be connected in five different basic topologies, which are series-series (SS) (see Fig. 1), series-parallel (SP), parallel-series (PS), parallel-parallel (PP) and LLC compensations topologies [7]. Resistances of the transmitter and receiver coils are R1 and R2 respectively. Self-inductances of the transmitter and receiver coils are L1 and L2 respectively. M represents the mutual inductance between the transmitter and receiver coils. Resonant capacitances of primary and secondary tanks are C1 and C2 respectively [6-9].

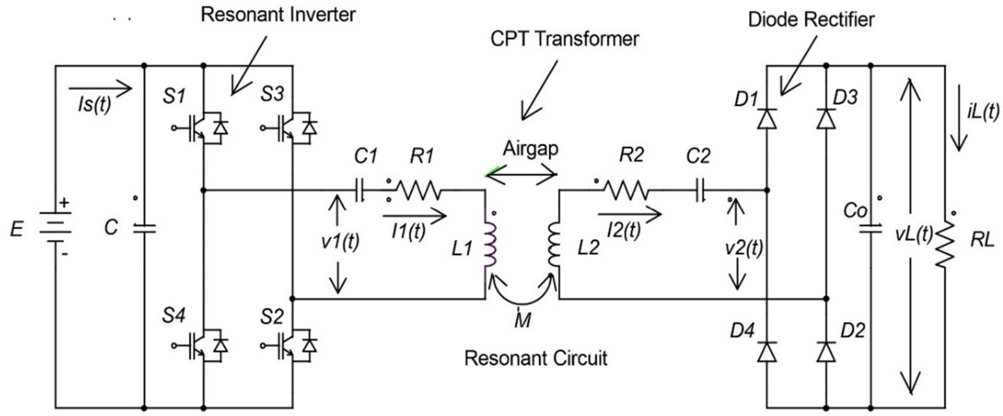


Fig. 1 A WPT system with series-series (SS) compensation topology

III.IMPROVING EFFICIENCY OF A WIRELESS POWER TRANSFER SYSTEM BY INCREASING COIL-WIDTH

It has been observed that mutual inductance can also be improved by extending the coil-width of a WPT system without using compensation topology. In this paper, an attempt has been made to improve the mutual inductance/coupling coefficient by increasing the coil-width of the transmitting and receiving windings thereby improving the overall efficiency of the system [10]. A WPT system with variable coil-widths has been modelled by using Maxwell finite element (FE) tool [11].

IV.IFINITE ELEMENT MODEL AND RESULT ANALYSIS

In this section, effect of change of coil-width on mutual inductance M and coupling coefficient k of a WPT system has been investigated (see Fig. 1). FEM analysis of the proposed system has been conducted using Maxwell finite element tool. Fig. 2 shows the FEA simulation schematic of the proposed WPT system. In FEA simulation, at a constant air gap of 10 cm and lateral misalignment of 2 cm, an initial width of 5 cm for the both transmitter and receiver coils has been considered. Then, the width of the both coils has been increased to 10 cm and 15 cm respectively. Corresponding mutual inductances and coupling coefficients have been shown in Table 1. Flux density distributions for variable coil-width are given in Fig. 3. From all the simulation results, it has been observed that the mutual inductance and coupling coefficient improves as the width of the coil increases.

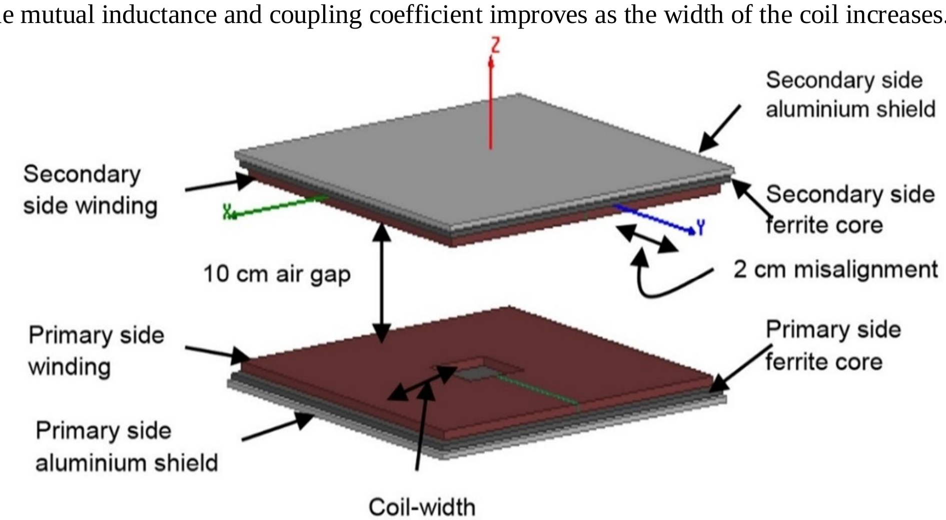
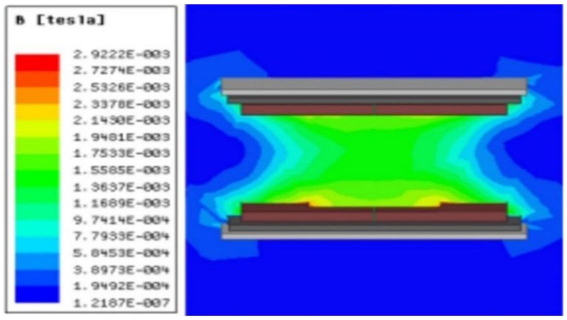
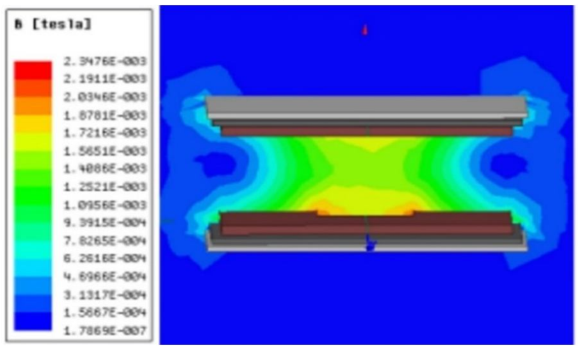


Fig. 2 FEA simulation schematic of the proposed WPT system

At the coil-width of 5 cm (minimum coil-width), the mutual inductance and the coupling coefficient are 5.402 uH and 0.162 respectively, which are quite low for a WPT system. When coil-width is increased to 10 cm, mutual inductance and the coupling coefficient are 11.963 uH and 0.305 respectively. In addition, when coil-width is increased to 15 cm, mutual inductance and the coupling coefficient are 20.448 uH and 0.434 respectively (see Table 1). Therefore, by increasing the coil-width, the mutual inductance as well as the coupling coefficient of a WPT system can be enhanced to improve the overall power transfer efficiency (PTE) of the system.



(a)



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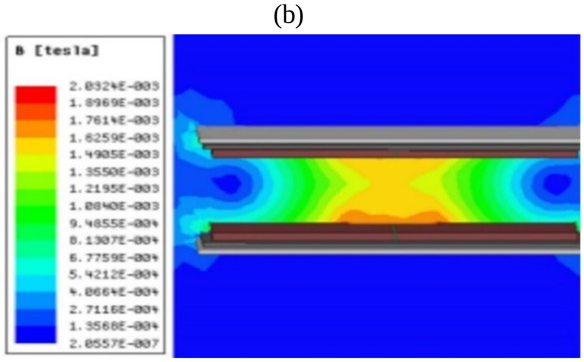

(c)

Fig. 3 Flux density distribution of the proposed WPT system at variable coil-width: (a) 5 cm coil-width, (b) 10 cm coil-width, (c) 15 cm coil-width

TABLE 1
MUTUAL INDUCTANCES AND COUPLING COEFFICIENTS AT VARIABLE COIL-WIDTH

Coil-width [cm]	Mutual inductance [μH]	Coupling coefficient
5.0	5.402	0.162
10.0	11.963	0.305
15.0	20.448	0.434

V. CONCLUSIONS

In this study, a WPT system with large air gap has been proposed for improving its efficiency using increased coil-width. It has been shown that with the increased coil-width, mutual inductance and coupling coefficient improve considerably thereby improving the overall performance of the system. However, there is a limit for extending the coil-width, beyond which mutual inductance or coupling coefficient does not improve significantly. The present concept of design for a WPT system can be applied to low as well as high power applications.

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