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Comparison of Maximum Transmission Efficiency and Magnetic Flux Leakage for Different Coupling Coils in Inductive Power Transfer Systems

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***Abstract* – Nowadays, inductive power transfer technology is widely considered for the charging of electric vehicles due to environmental pollution. The most important part of this system is how to design coupling coils with high efficiency and low magnetic flux leakage. The present work aims at comparing the maximum transmission efficiency and the magnetic flux leakage for different coupling coils in an inductive power transfer system. Here, four typical shaped coils (circle, square, double D and bipolar) are studied and compared in the simulation and the experimental aspect. The transmission efficiency and magnetic field distribution are relevant to different shaped coils as well as the variation of the misalignment between the coils.**

Index Terms - Inductive power transfer, Maximum transmission efficiency, Electromagnetic compatibility

I. Introduction

Inductive power transfer (IPT) has recently received increasing attention for electric vehicles due to a growing concern for the air pollution produced by conventional powered cars. Nowadays, electric vehicles (EVs) are equipped with large batteries that must be efficiently and rapidly recharged. These batteries can be charged via IPT technology to increase comfort and electrical safety in the charging process. So it is necessary to consider the transfer efficiency and the magnetic field leakage for an IPT system.

In order to design an effective IPT system, some reviews summarize and discuss different structures and shapes of the coils [1]. In [2], a simulation study was carried out to explore the variation of the coupling coefficient for different air-cored coil configurations under different air gaps and coil misalignments. However, it does not study the magnetic flux leakage around the coils for electromagnetic safety. Reference [3] provided several criteria such as the maximum transfer efficiency and the magnetic flux leakage to study the effect of coil shapes, but the coils are air-cored. Reference [4] only compared coupling coefficient of differently shaped coils with ferrite plates under different misalignments. In a word, the literature does not consider the maximum transfer efficiency and the magnetic flux leakage for different coupling coils with ferrite plate at the same time.

In this paper, the main aim is to study the maximum transmission efficiency and magnetic flux leakage for differently shaped coils with ferrite plate. Four differently shaped coils (including circular coils, square coils, bipolar (BP) coils, and double D (DD) coils) have been proposed in small scales simulations and experiments to save computational time and the cost of the coupling systems. Moreover, different coil configurations are analyzed on the maximum transmission efficiency according to the effect of the misalignment between the transmitter and the receiver, and the magnetic flux leakage near the coupling systems.

II. Inductive power transfer system

The block diagram of an inductive power transfer system for electric vehicles is provided in Fig.1.

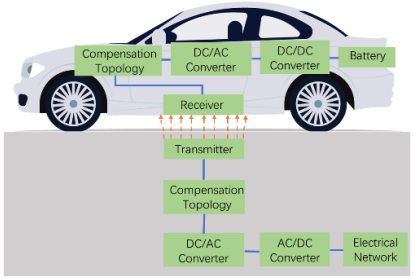
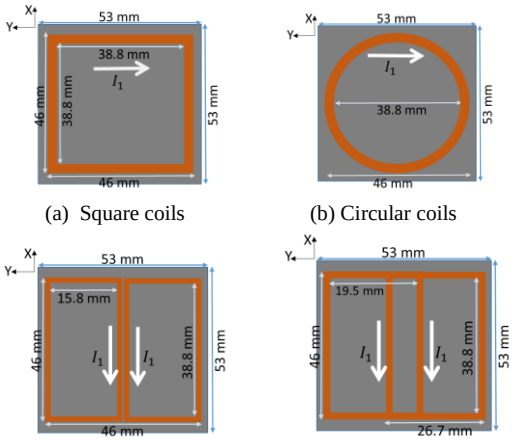


Fig. 1 Black diagram of IPT systems.

The IPT system consists of several converters and resonant compensation networks for the transmitter side and the receiver side. The electrical network provides the voltage to the transmitter through the converters. The magnetic field produced by the transmitter induces an alternating field in the receiver. The AC power is then rectified at the receiver side in order to charge the battery. Compensation networks are added to the transmitter and the receiver to create the resonant case and reduce additional losses.

The specifications of an IPT system include the air gap between the transmitter and the receiver, maximum allowed size and a specific shape for the transmitter and the receiver.

Typical coil shapes for the transmitter and the receiver in IPT systems include circular, square, BP and DD. However, a realization of real-scale coils of different coupling coils consumes a lot of time and is costly, especially considering the price of the materials used (wire and ferrite). To save time and cost, the coils here are not considered in real sizes but miniaturized on a scale of 1:10 [4]. The circular coils, square coils, DD coils and BP coils with ferrite plates in small-scale sizes are shown in Fig.2. The current inside the transmitter is the same for different coupling coils. The coils are made of Litz wires with six turns distributed in 2 layers. The width of the coil is 3.6 mm and the thickness is 2.4 mm. The thickness of the ferrite is 2 mm and its relative permeability is 2500. The air gap between the transmitter and the receiver is 15 mm.



(a) Square coils (b) Circular coils

(c) DD coils (d) BP coils

Fig. 2 Small scales of the coils.

III. ANALYSIS OF DIFFERENT COUPLING COILS

A. *Electrical parameters*

The equation to calculate the maximum transmission efficiency $\eta_{\max}$ can be simplified as below when the product of the coupling coefficient k and the inductor quality factor Q is higher than 2, and the coils are identical for the transmitter and the receiver [5]:

$$\eta_{\max} = \frac{(kQ)^2}{\left(1+\sqrt{1+(kQ)^2}\right)^2} \approx 1-\frac{2}{kQ} = 1-\frac{2\sqrt{R_1R_2}}{w_0M} = 1-\frac{\rho}{\pi f_0 S}\frac{l}{M} \qquad (1)$$

Where $k=\frac{M}{\sqrt{L_1L_2}}$, l is the length of the conducting wires for different coupling coils, S is the cross-sectional area of the conducting wires, ρ is the resistivity of the wires made of copper, the frequency f_0 is equal to 85 kHz and M is the mutual inductance between the coils.

Fig.3 shows the variation of the maximum transmission efficiency with the misalignment along the X/Y axis (defined in Fig.2) leads to the same result. When they are all in the aligned positions, the value from the circular coupling coils is the maximum among these coupling coils. With the misalignment increasing, the square coupling coils have a better tolerance compared to other coupling coils.

B. *Magnetic flux leakage around the coupling coils*

To evaluate the magnetic flux leakage near the coupling systems, the observation part is to be above the receiver with a ferrite plate 32 mm, as shown in Fig.4 (a). The distribution of the magnetic flux leakage is hereby reported in Fig.4 (b) when the current amplitude inside the primary coil is 0.21A and they are aligned.

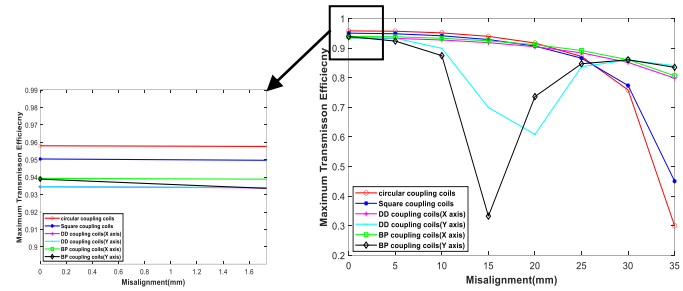
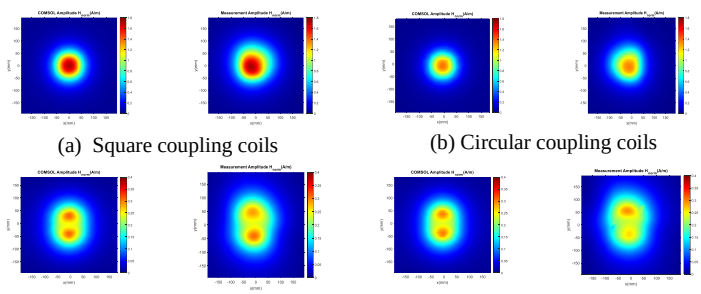


Fig. 3 Impact of misalignment on maximum transmission efficiency for different coupling coils.



(a) Square coupling coils (b) Circular coupling coils

(c) DD coupling coils (d) BP coupling coils

Fig. 4 Measurement of magnetic field distribution for different coupling coils.

IV. CONCLUSION

In this work, how to choose the shape of the coupling coils depends on a trade-off among the transmission efficiency, the tolerance to the misalignment and the magnetic flux leakage. Square coupling coils are chosen for the further study due to the tolerance to the misalignment, but for the real scale of coils, an electromagnetic shielding needs to be considered for the human safety.

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